

EFFECT OF CHEMICAL INJECTIONS ON PRESSURE DROP THROUGH A
FIBROUS DEBRIS BED

A Thesis

by

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ABSTRACT

This thesis examines five chemical solutions that are considered to be representative of the solution created in the containment sump during a postulated LOCA (loss of coolant accident) at a Pressurized Water Reactor (PWR) power plant. In order to compare these solutions this study examines the head-loss response they produce through a prototypical sump strainer covered with a conventional fibrous debris bed.

Eleven experiments were conducted at TAMU's vertical loop facility and four tests were selected for the purposes of this study. The test procedure started with a conventional debris bed being formulated on the sump strainer. Then followed the injection of the chemical solutions. The pressure drop through the debris bed and the approach velocity were monitored and recorded, among other parameters of interest.

The analysis of the results provided important insight on the relationship between the characteristics of the solutions and the response of the conventional debris bed. The results of this analysis provide valuable guidelines on the choice of chemical solutions to be used in further experimental research.

DEDICATION

I dedicate this work to my family and especially my father Elias and my brother Konstantinos. Without their help and constant support this work would not have been possible.

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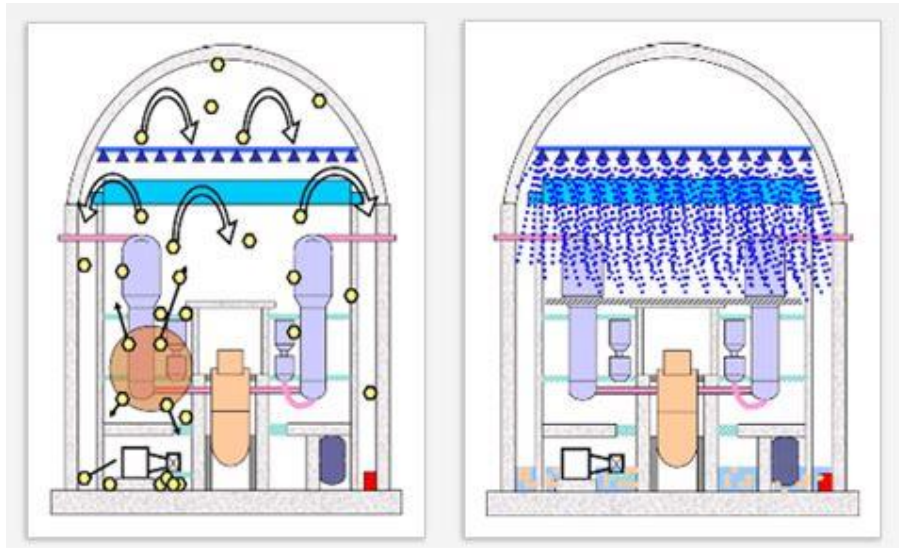
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1 INTRODUCTION

In nuclear power plants, fibrous media have been used to insulate the reactor vessel and the pipe lines in order to prevent heat loss from the system and protect the containment structures and other components from thermal stress. Though fibrous media provide efficient thermal insulation, they have been focused on, as a source of a safety issue. Every nuclear power plant is required by regulation (10 CFR 50.46) to have an Emergency Core Cooling System (ECCS) to mitigate a design basis accident (DBA). The ECCS can be affected by fibrous debris generated during a Loss-of-Coolant Accident (LOCA) which is the DBA of Light Water Reactors (LWRs).

In the event of a loss-of-coolant accident (LOCA) at a nuclear power plant, thermal insulation in the vicinity of the pipe break may be dislodged and torn by the impingement of the high-energy steam/water jet. The insulation material is usually made of fiberglass, which generates fibrous debris during the accident. Debris accumulation on the containment sump strainer may cause a loss of net positive suction head (NPSH) which can affect the ECCS pump performance, while debris that penetrates through the strainer may clog inside the reactor core or other components on the coolant flow path (in-vessel effects). These issues potentially affect the cooling capability of the reactor core in case of a LOCA.

The containment sump collects reactor coolant leaked from breaks and from containment sprays following a LOCA (see Figure 1.1 [1]); it then serves as the water source to support long-term recirculation.



A)

B)

Figure 1.1 The sources of coolant water (a) Break, (b) Sprays

(Photo Source: <http://www.nrc.gov/reactors/operating/ops-experience/pwr-sump->

[performance/safety-concern.html](http://www.nrc.gov/reactors/operating/ops-experience/pwr-sump-performance/safety-concern.html))

Since the debris collected in the containment sump can block or damage the ECCS pumps and pipe lines, the containment sump is equipped with strainers to prevent debris from entering the pump suction lines as shown in Figure 1.2 [2] and Figure 1.3.

[3]



Figure 1.2 Containment sump strainers

(Photo Source: <http://www.nrc.gov/reactors/operating/ops-experience/pwr-sump-performance/function-containment-sump.html>)

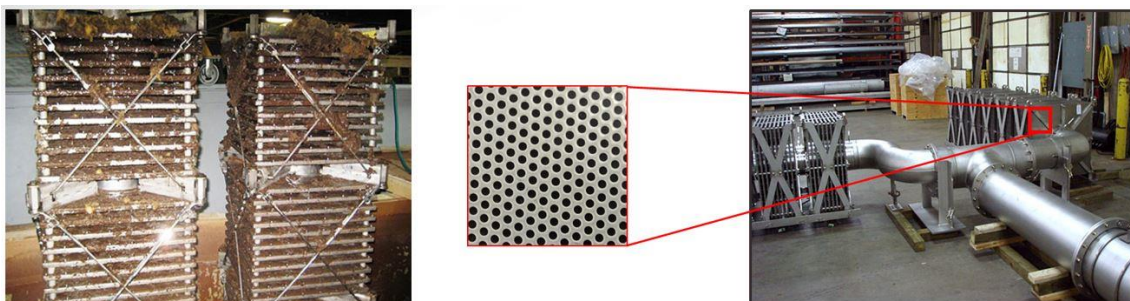


Figure 1.3 Clogged strainer (right). Clean strainer (left)

(Photo Source: http://www.pciesg.com/GSI-191_gallery.php)

The high temperature water collected in the containment sump carries with it fibrous debris used for insulation purposes along with other plant specific materials such as dirt, paint chips, reflective metallic insulation (RMI) etc. The high temperature

water can also corrode metallic structures located inside the containment thus creating plant specific corrosion produced solutions. These solutions can precipitate during the cooling of the re-circulation water and affect the pressure drop through the fibrous debris bed already deposited on the sump strainer.

On July 28, 1992, a spurious opening of a safety valve at Barsebick Unit 2, a Swedish BWR, resulted in clogging of two ECCS pump suction strainers leading to loss of both containment sprays within one hour after the accident. The release of steam dislodged mineral wool insulation, pieces of which were subsequently transported by steam and water into the suppression pool located at the bottom of the containment.

Instances of clogging of ECCS pump suction strainers have also occurred at U.S. plants, including two instances that occurred at the Perry Nuclear plant, which is a BWR/6 with Mark III containment. The Barseback-2 event demonstrated that larger quantities of fibrous debris will reach the strainers than would have been predicted by models and analyses developed for resolution of USI A-43.1, 2. The instances at Perry suggested that filtering of small particles, e.g., suppression pool sludge, by the fibrous debris bed will result in increased pressure drop across the strainers.

Given these precursor events, NRC staff initiated analyses to estimate potential for loss of NPSH of the ECCS pumps in a BWR due to clogging of suction strainers by a combination of fibrous and particulate debris. In October 1995 study NUREG/CR-6224 by (Zigler et al., 1995) [4] was published which evaluated the potential for LOCA generated debris and the probability of losing long term recirculation capability due ECCS pump suction strainer blockage. The calculated point estimate of core damage

frequency (per Rx-year) due to blockage related accident sequences for the reference BWR ranged from $4.2\text{E-}06$ to $2.5\text{E-}05$. Part of this study was to develop a head loss model to estimate the pressure drop across the strainer due to debris bed buildup. The overall loss of NPSH margin frequency (per Rx-year) was estimated to be $1.58\text{E-}04$. The overall pipe break frequency was estimated to be of $1.59\text{E-}04$. At the time it seemed that all LOCA's would lead to loss of NPSH margin for the ECCS pumps which is off-course unacceptable.

Since then many more studies and papers have been published on the issue, known with the general term: GENERIC SAFETY ISSUE 191 (GSI-191). The Generic Safety Issue (GSI)-191 study addresses the issue of debris accumulation on the PWR sump screen and consequential loss of ECCS pump net positive suction head (NPSH).

In all of the studies pertaining to this issue an intrinsic part of the analyses is to establish an accurate theoretical or semi-theoretical correlation of evaluating the loss of (NPSH) related to the accumulation of debris on the sump strainer. In study NUREG/CR-6224 [4] the NRC developed a semi-theoretical head-loss correlation for predicting head loss through fiber beds based on fundamental principles of porous media filtration and hydraulics. The correlation was shown to provide an accurate characterization of head loss across LOCA-generated debris beds composed of randomly assembled fragments of fiberglass insulation. This correlation is known as the NUREG_6224 Correlation.

The general equation, valid for laminar, transient, and turbulent flow regimes, is formulated as:

$$\frac{\Delta H}{\Delta L_0} = Units \{ [3.5 S_v^2 (1 - \varepsilon_m)^{1.5}] \mu U + 0.66 S_v \frac{(1 - \varepsilon_m)}{\varepsilon_m} \rho_w U^2 \} \left(\frac{\Delta L_m}{\Delta L_0} \right) \quad (1.1)$$

(NUREG_6224 Correlation)

where Units = 1 for SI units

However in conjunction with English Units we have:

S_v is specific surface area (ft²/ft³)

μ is dynamic viscosity (lbm/s-ft)

U is velocity (ft/s)

ΔH is head loss (ft-water)

ρ_w is water density (lbm/ft³)

ΔL_0 is the fiber bed theoretical thickness (in.)

ΔL_m is the actual bed thickness (.in)

The unit conversion factor becomes: Units = $4.1528 \times 10^{-5} \frac{ft-water/in}{lbm/ft^2 s^2}$

The mixture porosity, ε_m can be given as:

$$\varepsilon_m = 1 - (1 + \frac{\rho_f}{\rho_p} \eta) (1 - \varepsilon_0) \frac{\Delta L_0}{\Delta L_m}$$

where,

ρ_f is fiber density (175 lbm/ft³ or 2803 Kg/m³)

ρ_p is sludge particle density (324 lbm/ft³ or 5190 Kg/m³)

η is sludge to fiber mass ratio

ε_0 is the theoretical bed porosity

ε_0 and ΔL_m (in ft) can be calculate as:

$$\varepsilon_0 = 1 - c_0/\rho_f$$

$$\Delta L_m = c_0/c \Delta L_0$$

where,

c_0 is the 'as-fabricated' packing density (lbm/ft³)

c is the actual packing density (lbm/ft³)

The work by Igmanson et al [5] suggests that the fiber bed packing density dependence on the head loss can be correlated using a regression fit of the form:

$$c = \alpha c_0 \left(\frac{\Delta H}{\Delta L_0} \right)^\gamma$$

where, $\alpha = 1.3$, $\gamma = 0.38$

The homogeneous specific surface area of the bed is determined from the specific surface areas of the individual components. A debris bed likely will consist of multiple types of fibers and particulates, each with their respective specific surface area. The homogeneous-bed-specific surface area for a bed consisting of one type of fiber and one type of particulate is given by:

$$S_v = \left[\frac{1 + \frac{\rho_f}{\rho_p} \eta \frac{S_{vp}}{S_{vf}}}{1 + \eta \frac{\rho_f}{\rho_p}} \right]$$

where,

S_{vf} is the fiber specific surface area (ft²/ft³),

S_{vp} is the particulate specific surface area (ft²/ft³)

The solution of the general NUREG/CR-6224 correlation and its supporting equations requires an iterative solution.

In addition, there is a practical limit to the fiber bed compression whenever significant particulate is embedded in the fiber matrix. The particulate cannot be compressed beyond its granular density, referred to herein as the sludge density (e.g., 65 lbm/ft³ for BWR suppression pool iron oxide corrosion products). Therefore, whenever the bed density reaches the following limit, further compression ceases.

$$\Delta L_m = \Delta L_0 \frac{c_0}{c_{sludge}} (\eta + 1)$$

where, c_{sludge} is the sludge density

When the correlation is applied to a debris bed that does not contain significant fiber (e.g., CalSil-only debris), the fiber compressibility correlation does not apply and the porosity equation must be simplified. The bed compressibility is set to one, the bed-specific surface area is that of the particulate, and the bed porosity is determined from the particulate sludge density:

$$\varepsilon_o = 1 - c_{sludge}/\rho_p$$

where, ρ_p is the density of each individual particle.

In a more recent study, prepared for the Division of Engineering Technology, Office of Nuclear Regulatory Research U.S. Nuclear Regulatory Commission by the Los Alamos National Laboratory (NUREG/CR-6874) [6], 6224 correlation was criticized for not addressing the full range of potential debris characteristics postulated for accidents in pressurized-water reactors (PWRs). Specifically the head loss associated with CalSil insulation in combination with NUKON and reflective metallic insulation (RMI) materials. NUREG/CR-6874 evaluated the suitability of the 6224 correlation for CalSil

in combination with other debris. In addition, the tests examined the effect of a range of applicable parameters for typical U.S. PWR plants during recirculation cooling operation, including screen approach velocities, water temperatures, and debris bed mixtures of CalSil and fiber/RMI.

The above discussion underlines the fact that plant specific conditions will produce different solutions during a LOCA which in turn behave differently when circulating through the fibrous debris bed which is typically created during the accident on the sump strainer. Semi-empirical correlations such as correlation-6224 need to be adjusted to plant specific parameters in order to describe the phenomena of interest correctly. It is thus important to identify these plant specific parameters and the solutions they will produce as accurately as possible. Then formulate a procedure that will either re-create these exact solutions or identify suitable surrogates that will simulate these plant specific solutions in an experimental environment and use them for research purposes.

2 SCOPE

Texas A & M University (TAMU) in co-operation with ALION performed 11 head-loss tests to quantify the effects of injection of various solutions on a pre-formed fibrous debris bed of different composition and characteristics, on a prototypical Pressurized Water Reactor (PWR) sump strainer.

Results from this test program will support the GSI-191 resolution for different nuclear power plants which may require large-scale head loss tests designed under more realistic geometrical conditions.

Table 2.1 lists the tests conducted during the program, providing a short description of the test conditions and test purpose.

Table 2.1 Review of experiments

EXPERIMENT NAME	EXPERIMENT PURPOSE
HT-1001	Establish the prototypical conventional debris bed, that will be used to assess various chemical precipitate head loss
HT-1101	Quantify the response of in-situ aluminum oxyhydroxide (AlOOH) for comparison to WCAP-16530-NP-A AlOOH surrogate.
HT-1102b	Quantify the response of in-situ aluminum oxyhydroxide (AlOOH) for comparison to WCAP-16530-NP-A AlOOH surrogate.
HT-1103	Quantify the response of WCAP-16530 Aluminum Oxyhydroxide (AlOOH) surrogate and compare to Test 1102b.
HT-1104	Quantify the response of a representative salt surrogate and compare to Tests 1102b and 1103, which are the same as this test except for the chemical surrogate.
HT-2001	Quantify the response of a representative salt surrogate with a conventional debris bed that differs from Test 1104 and Test 1103.
HT-3001	Yield insights to the effects of in-situ chemical precipitate nucleation in the conventional debris bed.
HT-1201	Replicate Test 1104 but with a different chemical precipitate concentration during precipitate formation as noted below:

Table 2.1: Continued

EXPERIMENT NAME	EXPERIMENT PURPOSE
	<ul style="list-style-type: none">• Test 1104 – In-situ Chemical Concentration, 0.1759 g of AlOOH/L• Test 1201 – Alden Research Laboratory (ARL) Chemical Concentration, 2.1 g of AlOOH/L
HT-1201RE-1	Test 1201RE-1 is a replicate of Test 1201 which was terminated early due to large head losses prior to the injection of chemical precipitates.
HT-3001RE-1	Test 3001RE-1 is a replicate of the plan for Test 3001 with two additional procedural specifications. The actual test procedure for Test 3001 deviated from the planned test procedure due an unexpected head loss increase prior to the reduction of temperature and velocity. The purpose of Test 3001RE-1 is to yield insights to the effects of in-situ chemical precipitate nucleation in the conventional debris bed.
HT-1201RE-2	Test 1201RE-2 is the second replicate of Test 1201 which was terminated early due to large head losses prior to the injection of chemical precipitates. Test 1201RE-1, the first replicate of Test 1201, resulted in low conventional and chemical head loss. The expectation is to have a comparable or slightly larger head loss than Test 1104. The target chemical concentration during preparation is the only varied parameter between Test 1201RE-1 and Test 1104.

It is within this project that the scope of this thesis was formulated. This thesis aims to study the response of fibrous debris beds to chemical additions during typical flow conditions expected during a hypothetical LOCA at a PWR, and to provide insight on the selection of chemical solutions to be used for future testing. This study examines five solutions of different characteristics:

- In-Situ Corrosion product.
- WCAP-16530.
- Salt Surrogate (Type 1).
- Salt Surrogate (Type 2)
- Salt Surrogate (Type 3) (Alden Research Laboratory Recipe).

The analysis of the fibrous debris bed response will account for the pressure drop magnitude, the time-response and other visual observations, and will aim to identify differences and similarities between the debris beds behavior under the conditions investigated.

3 CONTENT

The following sections are included in this thesis:

- A description of the experimental facility used for conducting the experiments, including main geometrical information and instrumentation is provided in section 4. Selected and installed instruments are provided in Sub Section 4.5.
- Test preparations are described in section 6
- The experimental procedure adopted during the test activity and the monitoring system implemented is described in Section 7.
- The experimental results are shown in Section 8. Figure of merit for the comparison between the solutions is the pressure drop through the debris bed. Other important parameters such as flow approach velocity and temperature are discussed.
- Discussion of the results obtained and conclusions are provided in Section 10 of this study.

4 EXPERIMENTAL FACILITY

A detailed description of the experimental facility is provided in this section. The test facility is presented in Figure 4.1 and Figure 4.2. The test facility consists of the following main components:

- The head loss loop, where the solution is circulating.
- An open lid tank on top of the loop where the chemicals and the debris are injected.
- The test section, where the prototypical sump screen is located and where the fibrous debris bed is formed.
- Two corrosion tanks used to produce the base solutions and to prepare the in-situ corrosion products.
- Instrumentation used to measure the quantities of interest.

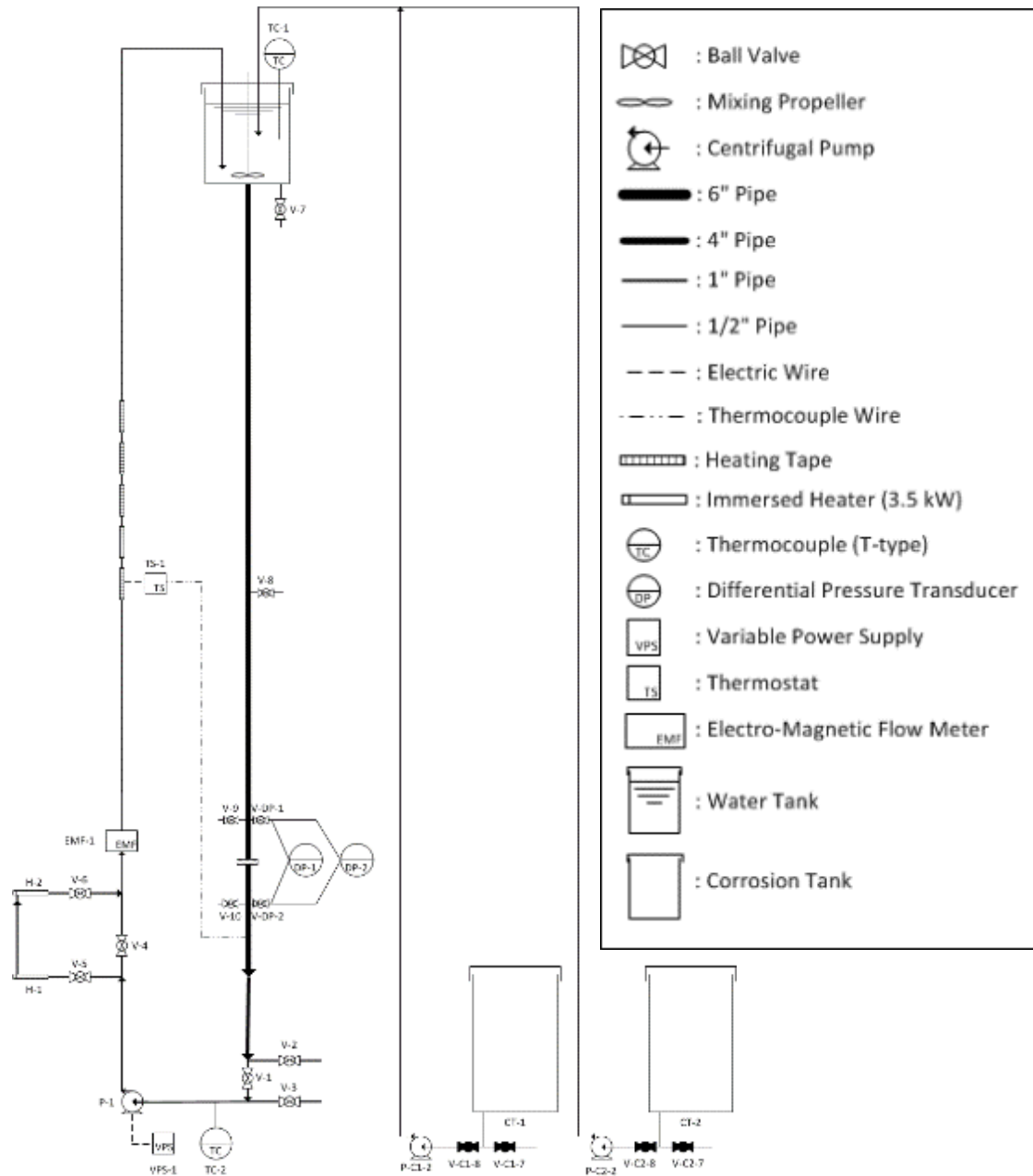


Figure 4.1 Schematic diagram of experimental facility

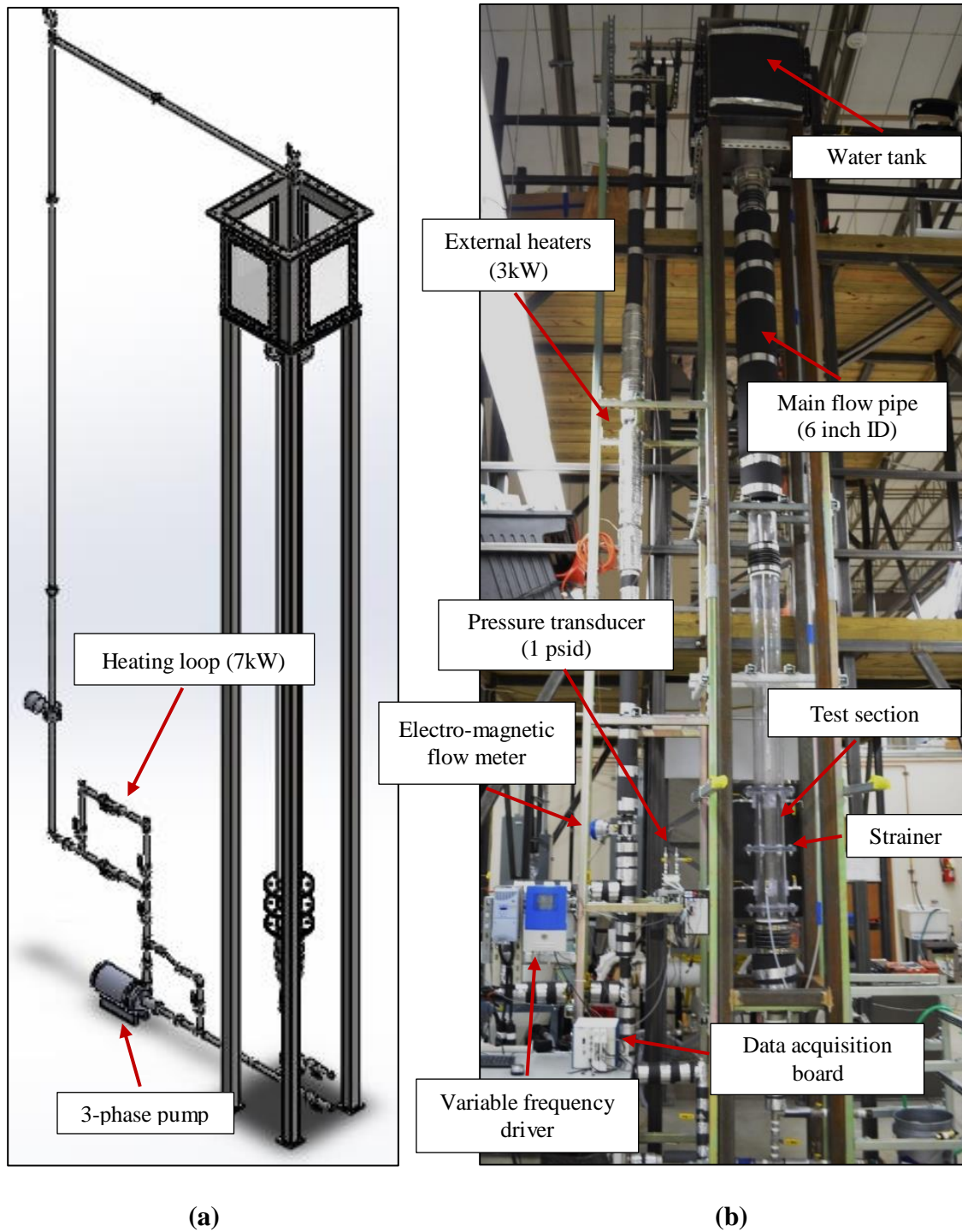


Figure 4.2 Picture of experimental facility: (a) Drawing, (b) Photo

4.1 Head Loss Loop

The facility was designed to operate at temperatures up to 85 °C. A set of two heaters (one internal and one external, see Figure 4.2) have been installed (total Power = 10 kW) to increase the temperature of the water in the loop up to the desired value. The lower portion of the Head Loss Loop is shown in Figure 4.3.

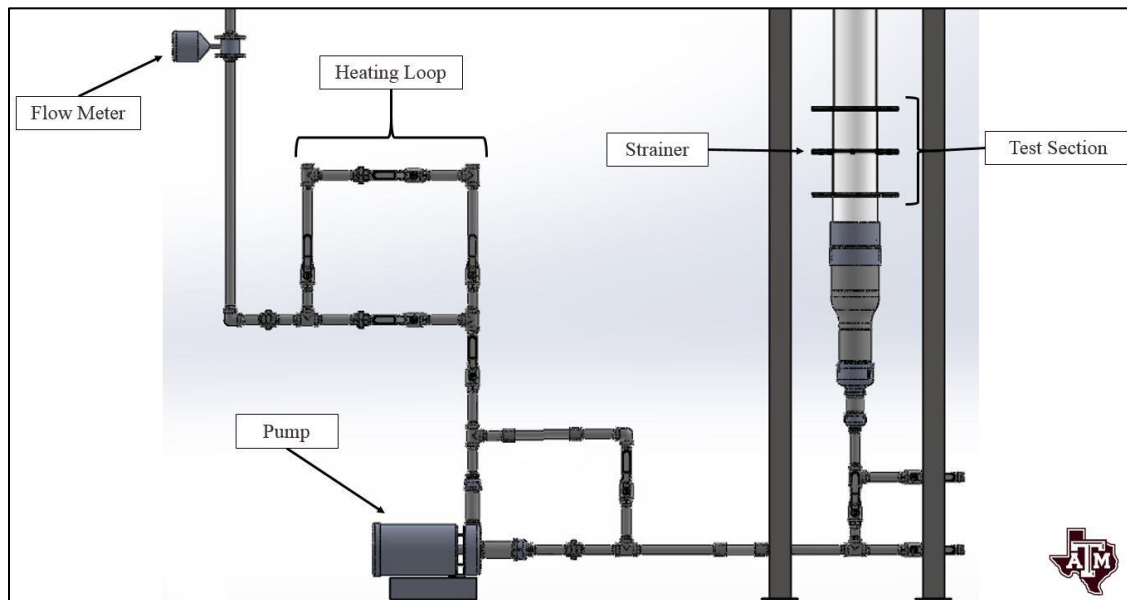
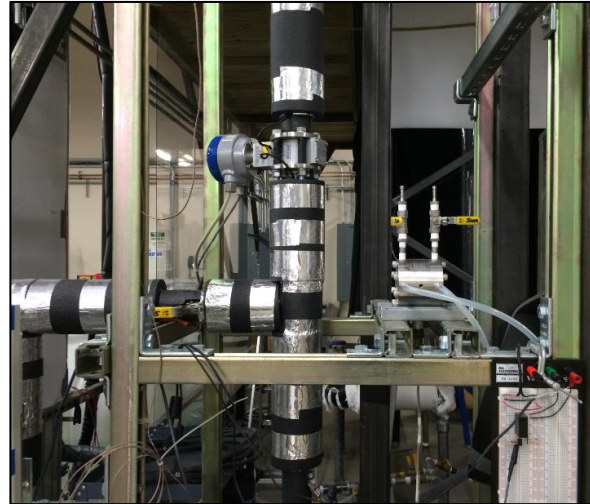


Figure 4.3 Lower portion off head loss loop

A thermostat controls the external heaters to maintain the temperature to the target ($\pm 3\text{ }^{\circ}\text{C}$). Cooling down is operated by natural convection. A stainless-steel centrifugal pump seen in Figure 4.4(a) provided the required volumetric flow rate in the test section to reach the desired approach velocity for low and high temperatures. An Optiflux-1300 magnetic flow meter (Krohne®) seen in Figure 4.4(b) was installed downstream of the pump to read the volumetric flow rate. The accuracy at the target flow velocity (0.01 ft/s or 0.003m/s) is 2 % of the reading.



(a)



(b)

Figure 4.4 3-phase stainless-steel pump (a) and electro-magnetic flowmeter & differential pressure transducer (b)

4.2 Water Tank

The water tank with a mixing propeller on top of the loop is shown in Figure 4.5. The main frame of the water tank was made of stainless steel. To allow visualization, polycarbonate windows were installed on three sides of the tank. The top of the tank was open to allow for chemical and debris injections. A stainless steel (SS304) mixing propeller was installed, $\frac{1}{2}$ inch NPT for the body and $\frac{3}{4}$ inch NPT for the arms forming a T-shape mixer and controlled by a time-adjustable relay that switched the direction of rotation. Debris batches and chemical batches were injected into the tank during the experiment. (Figure 4.6, Figure 4.7).

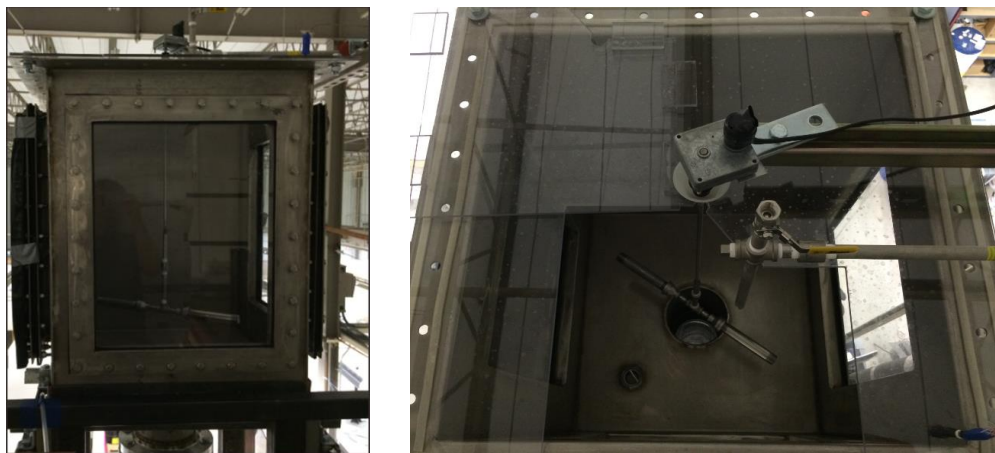


Figure 4.5 Water tank on top of loop.



Figure 4.6 Tank after debris batch B-1 was injected



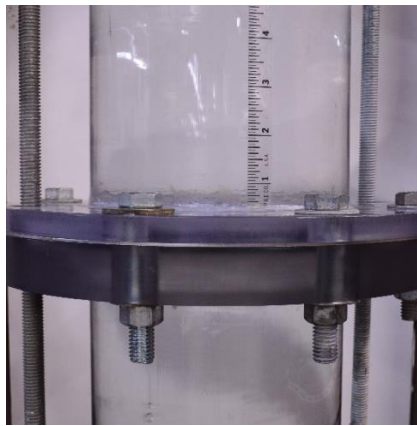
Figure 4.7 Injection of debris batch B-2 into tank

4.3 Test Section

The strainer (perforated stainless steel plate) presented in Figure 4.8 is fitted in the transparent Plexiglas test section between two polycarbonate tubes (6 inch ID, 6.5 inch OD). Plate thickness was 1.56mm, Pitch 3.96mm and hole diameter 2.42mm.



(A)



(B)



(C)

Figure 4.8 Strainer (A), Strainer fitted in plexiglas test section (B), (C)

4.4 Corrosion Tanks

The schematic diagram of the corrosion tank where the chemicals were prepared is presented in Figure 4.9. Both of the corrosion tanks used in the experiments can be seen in Figure 4.10. The corrosion tank is equipped with mixing pumps, heaters with controllers, thermocouples, level control and visualization system. The corrosion tank capacity is 100 gallons (378.5lt). The corrosion tanks are chemical compatible with a post-LOCA solutions. The maximum operating temperature is 85°C. Sampling ports are located at the bottom of the tanks (V-C2-9). The two corrosion tanks used are identical.

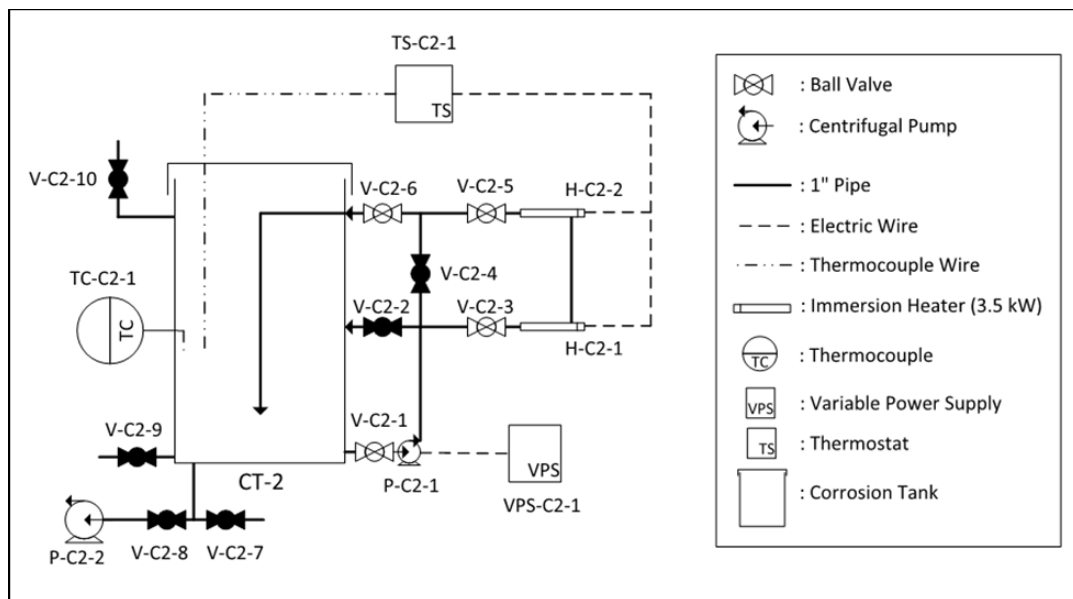


Figure 4.9 Schematic diagram of corrosion tank.



Figure 4.10 Picture of corrosion tanks.

4.5 Instrumentation

The test facility was equipped with one electro-magnetic flow meter, two differential pressure transducers, and four thermocouples (two in the head loss loop and one in each of the two corrosion tanks). This section provides relevant technical specifications of the instrumentation installed in the facility and the procedure adopted to verify the correctness of the installation and calibration.

4.5.1 Flow meter

An electro-magnetic flow meter (Optiflux-1300, Krohne®) was installed to measure the flow rate of the solution in the test loop. The manufacturer certified accuracy of the flow meter at different approach velocities is presented in Table 4.1.

Table 4.1 Electro-magnetic flow meter (Optiflux-1300, Krohne®)

Approach velocity	Accuracy
> 0.0015 m/s	0.5 %
0.003 m/s	1.7 %

To verify the flow meter performance at the low approach velocity of 0.06 cm/s, an additional laboratory calibration was conducted. The electro-magnetic flow meter was calibrated using ANSI/ASTM traceable cylinders. Flow rate was calibrated by

measuring 5 values between 0 m/s and 0.07 cm/s. The calibration curve of the Optiflux-1300 (S/N: S14307839) was obtained as shown in Equation 4.1.

$$U = 0.07065264 \times V_o - 0.0569976 \quad (4.1)$$

Where U is the approach velocity measured in cm/s and V_o is the voltage output signal from the flow meter in Volts. The velocity values obtained using the calibration curve were within $\pm 2\%$ range of the measured valued using calibration cylinder as shown in Figure 4.11.

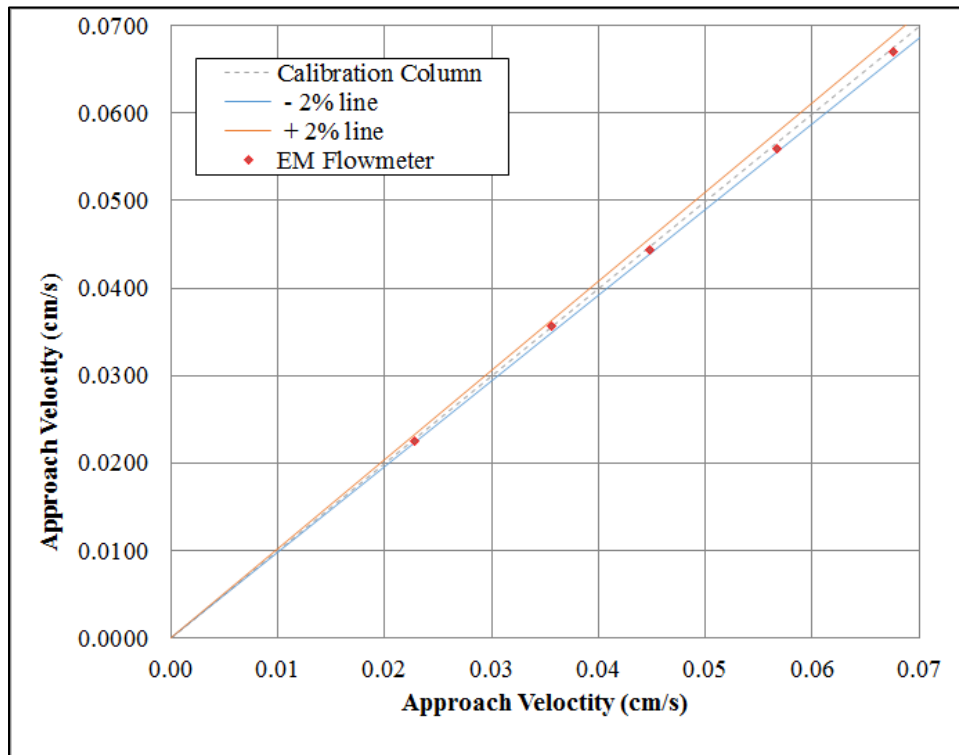


Figure 4.11 Flowmeter calibration result

4.5.2 Pressure transducers

Due to the wide range of pressure drop through the strainer encountered in this experiment and the need to measure that pressure drop accurately, two pressure transducers were utilized. One to measure pressure drops below 6.9 kPa and a second one to measure pressure drops above 6.9kPa.

The calibration curves provided by the manufacturer for the two differential pressure transducers were used to estimate pressure drop range. For the range obtained, the pressure transducers were re-calibrated using a manometer and a water column. The re-calibration took place to account for an offset observed in the initial calibration. During this calibration procedure, the output voltage from each transducer was recorded for multiple differential-pressure values as presented in Table 4.2 .

Table 4.2 Pressure transducer calibration data

Manometer Reading [in]	Manometer Reading [cm]	Pressure [kPa]	DP-1 (6.9 kPa)		
			Voltage [V]	Pressure drop Calibrated (kPa)	Error (%)
0	0.00	0.0000	0.0094549	-0.0039	N/A
4.92	12.50	1.2259	0.8765305	1.2331	0.5873
9.62	24.43	2.3973	1.70084595	2.4092	0.4940
14.52	36.88	3.6177	2.5497307	3.6204	0.0735
19.82	50.34	4.9387	3.48370855	4.9529	0.2859

Linear calibration Equation (4.2) was obtained to fit the pressure differential data:

$$P = 1.42303772 \times V - 0.01747525 \quad (4.2)$$

Where, P is the pressure drop measured in kPa, and V is the measured voltage signal in Volts. The error of the pressure reading of DP-1 with Eq. 4.2 was smaller than ± 0.014 kPa, which satisfied acceptance criteria of 0.021 kPa for the pressure drop less than 2.07 kPa. Figure 4.12 presents the calibrated data points bounded within $\pm 2\%$ error lines to show the linearity of the calibration curve, Eq. 4.2.

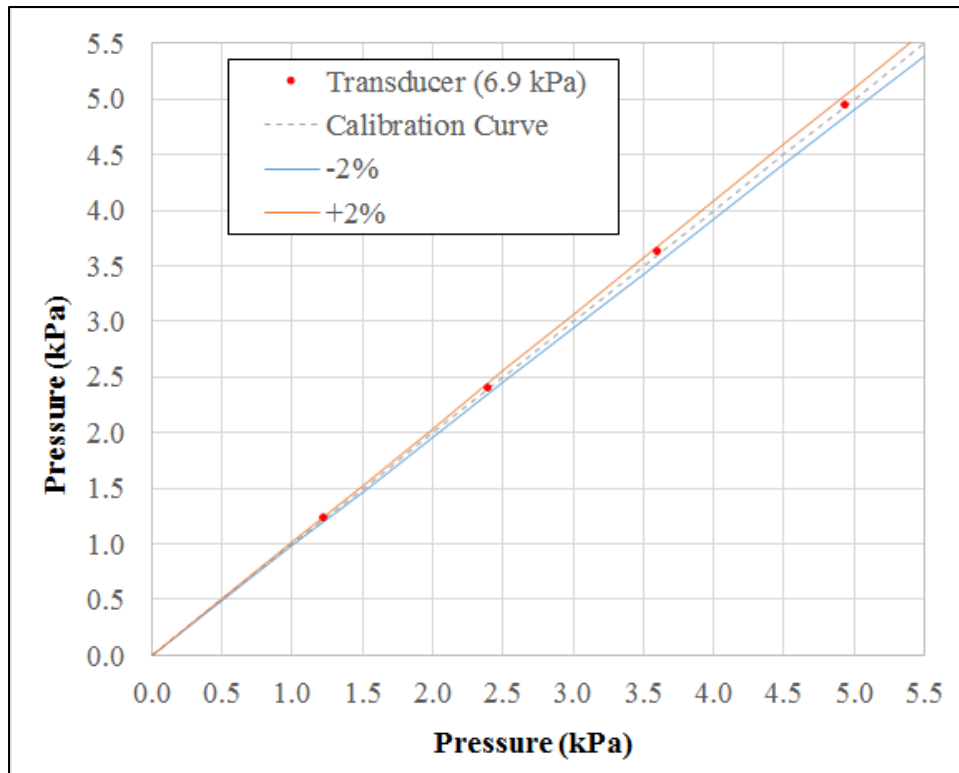


Figure 4.12 Calibration results for the 6.9 kPa range differential-pressure transducer

An additional calibration was performed on the 103.4 kPa range differential-pressure transducer, to cover the high pressure range of 8.96 to 26.89 kPa. This was done by varying the height of the water column on one side of the transducer. The output voltage from the transducer was recorded as presented in Table 4.3.

Table 4.3 Data for Omega transducer between 8.96 and 26.89 kPa

Water Level [cm]	Equivalent Pressure [kPa]	15-psid Transducer Voltage [V]	Pressure drop Calibrated (psid)	Error (%)
274.32	26.9016	1.29322945	26.9037	0.0078
213.36	20.9235	1.00566585	20.9234	0.0004
152.40	14.9453	0.7179193	14.9393	0.0407
91.44	8.9672	0.43095055	8.9713	0.0457

For the 103.4 kPa range differential-pressure transducer, Eq. (4.2) became:

$$P = 20.79652462 \times V + 0.009025241 \quad (4.3)$$

Error % in Table 4.3 clearly showed acceptable accuracy of the differential pressure transducer. Figure 4.13 presents the calibrated data points bounded within \pm 2% error lines to show the linearity of the calibration curve, Eq. 4.3.

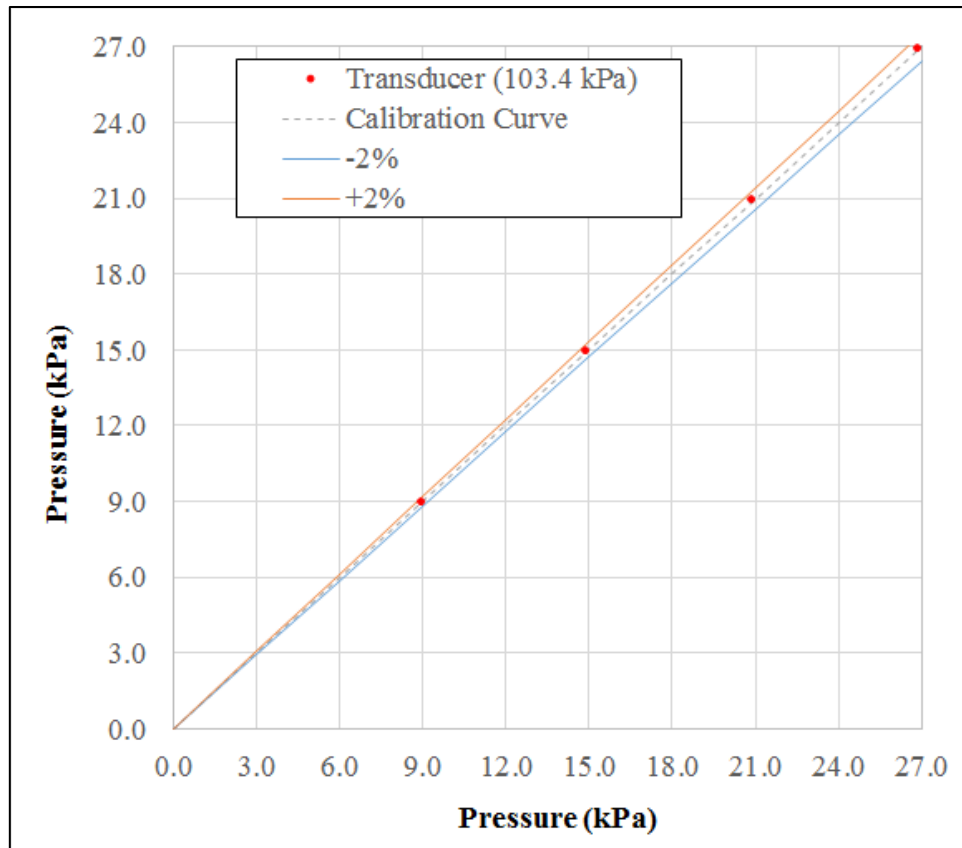


Figure 4.13 Calibration results for the 103.4 kPa range differential-pressure transducer

Hysteresis for both pressures due to temperature changes has been verified. This was completed by conducting a dedicated test with tap water only. Pressure drop through the clean screen was monitored at the beginning and the end of a temperature sweep in the loop. The following conditions were used:

Initial water temperature = 33.2 °C

Max water temperature = 66.2 °C

Final water temperature = 33.2 °C

The maximum temperature of 65 °C was reached in approximately 5.37 hours by turning on the heaters. The facility was then cooled down by natural convection and the final temperature of 33.2 °C was achieved in approximately 20 hours.

Table 4.4 shows the initial and final values of the pressure drop through the clean strainer for the two pressure transducers.

Table 4.4 Pressure transducer hysteresis verification

Pressure Transducer	Initial Pressure Drop (kPa)	Final Pressure Drop (kPa)
6.9 kPa (accuracy 0.007 kPa)	0.041	0.034
103.4 kPa (accuracy 0.028 kPa)	0.021	0.021

Hysteresis on pressure measurements due to temperature changes was not observed on the devices installed in the facility.

4.5.3 Thermocouples

Four K-type thermocouples were installed in the head loss loop and the two corrosion tanks. The thermocouples were connected to the data acquisition system through a combination of National Instrument (NI)-SCXI-1102 and SCXI-1030 terminals which allow automatic cold junction compensation (CJC). The thermocouples with the data acquisition system were validated using a Fluke 52-2 Thermocouple Thermometer (CSA certified, readability: 0.1 °C / accuracy: $\pm 0.05\%$ reading + 0.3 °C) as presented in Table 4.5.

Table 4.5 Thermocouples validation

Reference temperature (°C)	TC-1	TC-2	TC-C1-1	TC-C2-1
11.1	10.8	10.8	11.3	10.8
28.3	27.8	27.9	28.3	27.9
70.1	69.1	69.3	69.7	69.3
88.9	89.6	89.5	89.8	89.8

All thermocouples measured target temperatures within ± 1 °C.

5 TEST MATRIX

Four tests are selected and analyzed in this study. Tests: HT-1102b, HT-1103, HT-1104 and HT-1201RE-2. This section presents the test matrix shown in Table 5.1. The table includes the name of each test and the type of chemical solutions injected during each test. The total quantity of Aluminum injected into the loop during each test is also included.

In all the tests the conventional debris bed was formulated first by debris injection. The debris injection includes two distinct batches of two different solutions. Debris batch 1 (B-1) and Debris batch 2 (B-2). Both of them together formulate the conventional debris bed on the surface of the strainer and are common in all tests.

After the debris injection followed the chemical injection. The chemical injection also includes two distinct batches. Chemical injection 1 (C-1) and chemical injection 2 (C-2). C-1 and C-2 are of the same solution in each test but of different volume. The recipe used for their preparation varies between each test.

Last we had one final injection for three of the four tests.

Table 5.1 Test matrix

Test #	INJECTIONS		
	DEBRIS	CHEMICAL INJECTION	FINAL INJECTION
HT-1201b	CONVENTIONAL DEBRIS BED	IN-SITU ALUMINUM CORROSION PRODUCT (15g Al)	WCAP-16530 (4.5 g Al)
HT-1103		WCAP-16530 (15g Al)	N/A
HT-1104		SALT SURROGATE 1 (15 g Al)	SALT SURROGATE 2 (19.8 g Al)
HT-1201RE-2		SALT SURROGATE 3 (ARL RECIPE) (15 g Al)	WCAP-16530 (4.5 g AL)

6 TEST PREPARATION

The preparation of each test includes the following tasks:

- Preparation of the conventional debris bed.
- Preparation of the chemical injections.

6.1 Conventional Debris Bed Preparation

The conventional debris bed is created after the injection of Debris Batch 1 (B-1) followed by the injection of Debris Batch 2 (B-2) into the heated loop. B-2 is injected about an hour after B-1. Then they are left to circulate inside the loop for enough time (usually 17 hours) in order for the debris bed to be fully formed and stable. These debris batches simulate debris usually found in the containment of PWR's.

6.1.1 *Debris Batch 1 (B-1)*

The constituents of B-1 shown in Figure 6.1 are the following:

- Dirt (4.3g)
- Tin Powder (LX-2176) (28g)
- Acrylic Powder (LX-2180) (47.20g)
- CalSil (5.00g)

Dirt is a surrogate of the dirt found in PWR's. Tin powder is a surrogate for rust. Acrylic powder is a surrogate for paint and CalSil is a typically used insulation material.



Figure 6.1 Constituents of debris batch B-1

These constituents did not require any processing prior to the test except for CalSil. CalSil was prepared by blending the intact CalSil shells. Fines from the blended CalSil were selected and sieved as will be explained later. The sieved CalSil was mixed with other particulate and injected with batch B-1.

The constituents of the batch B-1, listed above, were individually prepared and weighted. The constituents were mixed and added to one liter of buffered borated (BB) DI water to prepare the batch B-1.

The CalSil quantity included in batch B-1 was prepared using a blender starting from the insulation shell. The CalSil (Thermo-12 Gold) quantity was prepared using a blender (Ninja BL610) starting from the insulation shells (Figure 6.2). Shells were broken in pieces of approximately 2" x 2" to fit into the blender container (capacity 2 l, max 2-3 pieces blended at the time).



Figure 6.2 Calsil insulation shells

The CalSil selected for the test was inspected and visually compared with a similar reference quantity produced by PCI to qualitatively confirm similar size and characteristics as shown in Figure 6.3.



Figure 6.3 Blended CalSil produced by TAMU (bottom) and produced by PCI (Top)

Based on the pressure drop and debris bed resulting from HT-1001, it was determined that the blended CalSil is to be sieved using a 1000 micron U.S. standard Sieve with a 1.00 mm opening as shown in Figure 6.4.

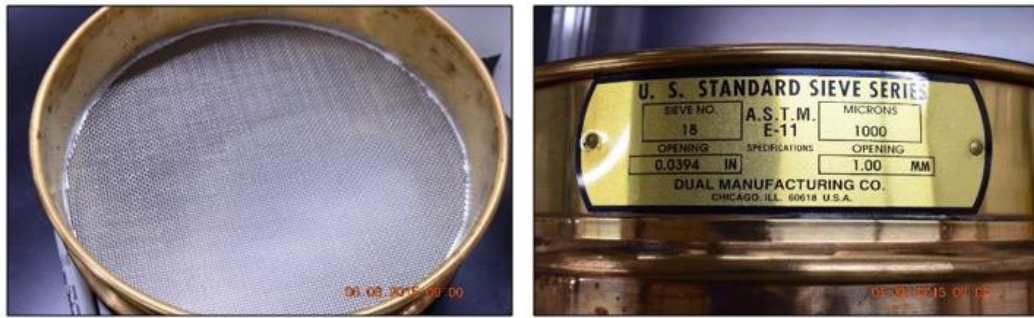


Figure 6.4 1000 Micron U.S. standard sieve

The final product was fine Calsil Powder, shown in Figure 6.5 and B-1 is shown in Figure 6.6.



Figure 6.5 Fine Calsil powder

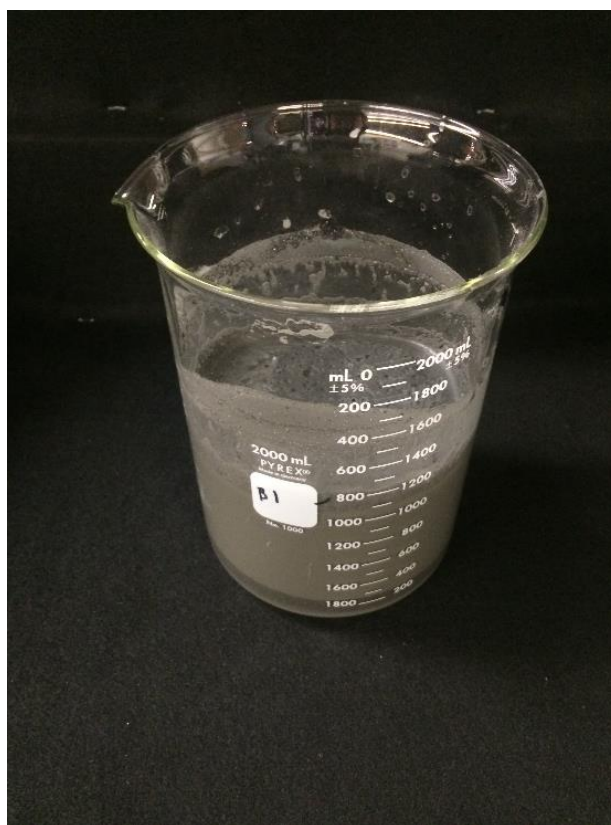


Figure 6.6 Debris batch B-1

6.1.2 Debris Batch 2 (B-2)

B-2 is created as fine debris using the TAMU modified NEI protocol. NUKON quantity is determined to be 6 g. NUKON is a typical fibrous insulation material used in PWR's. It constitutes the fibrous load in these tests. The samples are prepared with 4 gallons (15.14lt) of DI water.

Prerequisite Materials:

- Acculab VI-350 scale and calibration mass
- A preparation bucket (5 gallons)
- One side heat treated large mat of NUKON
- A high pressure water gun
- Scissors

The procedure is as follows:

1. Rinse the preparation bucket (total capacity = 5 gallons) and the lid using DI water.
2. Check the calibration of the scale and verify it works properly (Acculab® VI-350).
3. Cut a piece of NUKON from a one side baked large mat and weigh the required quantity on the scale.
4. Check that full thickness of the sample is preserved as shown in Figure 6.7 in order to conserve the original characteristics of the heat treated

mat. The mat is heat treated to simulate heat conduction during Plant operation.



Figure 6.7 NUKON mat and sample

5. In the preparation bucket, cut the pieces of NUKON to approximately one inch by one inch cubes with scissors.
6. Split cubes cleanly in half thickness.
7. Split the charred side into fourths. Split the clean side into eights.
8. Prepare high pressure washer without spray nozzle to use DI water.
9. Cover the preparation bucket with the lid. (Figure 6.8)

10. Fill the bucket to a depth of one 2.5 cm (approximately 1.9 lt) with DI water.
11. Place clean spray nozzle (40°) on high pressure water gun.
12. Randomly break the NUKON with the high pressure jet (1800 psi) until the bucket is filled up to 4 gallons. (Figure 6.8)

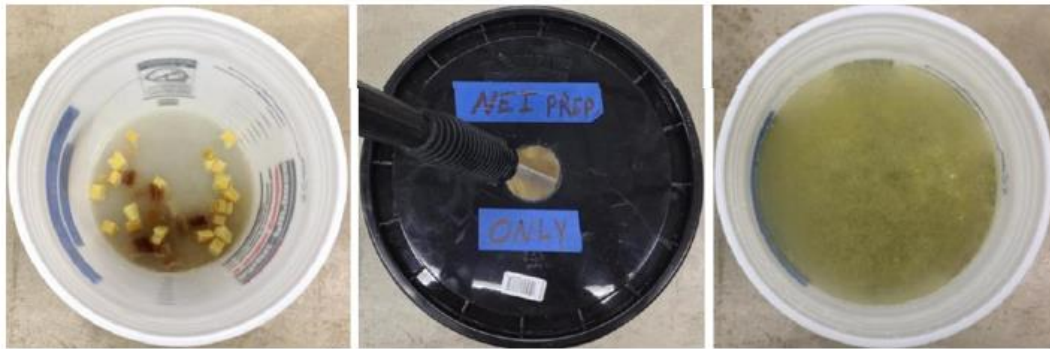


Figure 6.8 NUKON in preparation bucket

6.2 Chemical Preparation

The chemical precipitates introduced into the loop simulate the corrosion product created during an actual LOCA at a PWR. They are produced according to one of the following recipes:

- In-situ Aluminum corrosion product
- WCAP-16530
- Representative salt surrogate 1
- Representative salt surrogate 2
- Representative salt surrogate 3 (ARL)

6.2.1 *In-situ Aluminum corrosion product*

The generic preparation procedure for the in-situ aluminum corrosion product was conducted as follows:

1. The corrosion tank was filled with 189.3lt (50 gallons) of DI water and the measured electric conductivity ($24 \mu\text{S}/\text{cm}$) in the corrosion tank was confirmed to be the same value of the direct measurement of DI water filtering system.
2. Pump P-C2-1 was turned on and the chemicals were added (Boric Acid = 2177.8 g, NaTB = 618.6 g) to the tank to mix and fully dissolve in order for the solution to reach the target pH of 7.5 ± 0.1 . Once the chemicals were fully visually dissolved, a sample was take to measure the pH.
3. The lid of the tank was closed and the heaters were turned on until the target corrosion temperature of $85^\circ\text{C} \pm 3^\circ\text{C}$ was achieved.
4. Heaters and the pump were turned off and the lid was removed.
5. The aluminum foils (60.8 g, Ultra-corrosion-resistant 1100 Aluminum, 0.0015" thick) were placed in the tank (Figure 6.9).

6. The pumps and heaters were turned back on and the tank lid was closed.
7. The corrosion time for this test was defined based on previous shakedown tests performed under the same conditions and fixed to be 4 hours. After this corrosion time, the pump was turned off, and the aluminum foils were removed from the solution.
8. A sample was taken and acidified with HNO₃ for ICP measurement of Al concentration (79.86 mg/l).
9. The tank insulation was removed during the tank cooling. This process required approximately 2 days. The final solution is shown in Figure 6.10.
10. Once the solution in the tank reached room temperature, a sample for particle size was taken. Particle size distribution was measured and recorded as shown in Figure 6.11.

This recipe was used to prepare the chemical injections C-1, C-2 in test HT-

1102b



Figure 6.9 Aluminum foils inside corrosion tank



Figure 6.10 Aluminum corrosion product in tank.

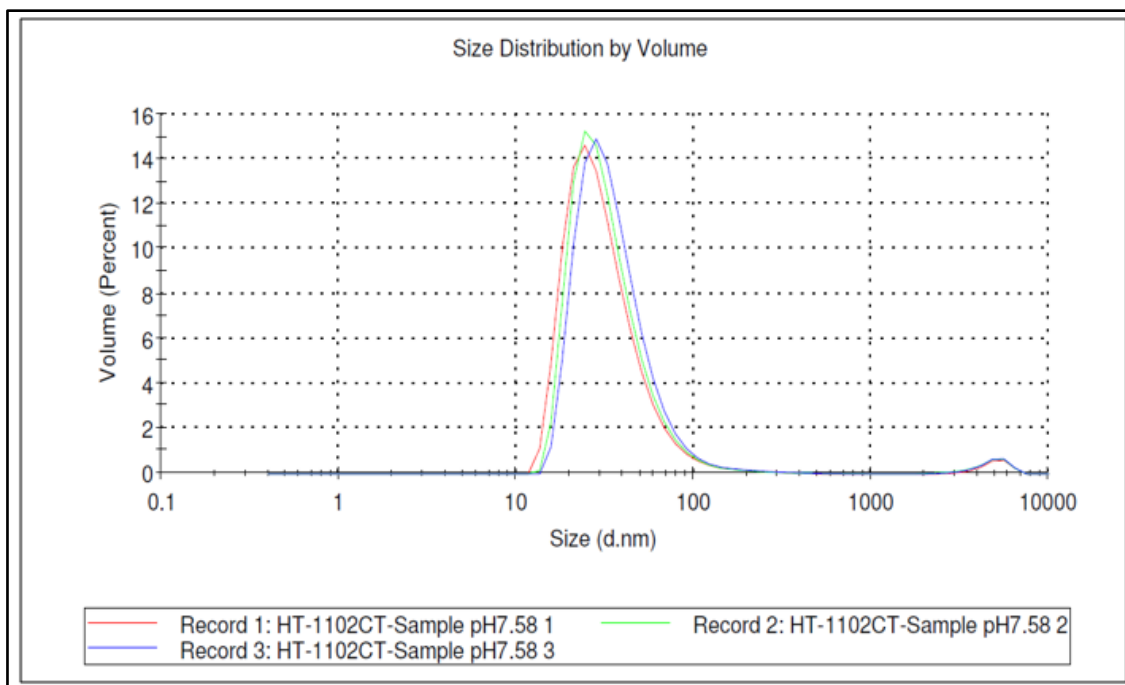


Figure 6.11 Particle size distribution by volume for in-situ chemicals (pH=7.5±0.1)

6.2.2 WCAP-16530

The WCAP solution was prepared following WCAP-AlOOH protocol [7] .

- 62.5g of $\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ were dissolved in 1.0 lt of DI water in the reactor and mixed manually by a stainless steel rod until fully dissolved.
- 20.00g of NaOH were added in the reactor and fully mixed manually for 10 min, obtaining a final solution of 10 g/lt AlOOH (4.5g/lt Al).

For more total corrosion product quantities are multiplied accordingly.

This recipe was used to prepare the final injection in tests HT-1102b and HT-1201RE-2.

A modified version of this recipe was also used in test HT-1103 to prepare the chemical injections (C-1, C-2).

- 206.25g of $\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ were dissolved in 1.5 lt of DI water in the reactor and mixed manually by a stainless steel rod.
- Also 66g of NaOH were added in the reactor and fully mixed manually for 10 min, obtaining a final solution of 22 g/lt AlOOH .

6.2.3 *Representative salt surrogate 1*

The target concentration of Al was 15 g of Al (equivalent to 33.3 g of AlOOH) per 189.3lt of solution. To achieve the target concentration the following recipe was followed:

1. Make borated buffer solution at target pH of 7.2 in the corrosion tank with 189.3lt. This solution is made by dissolving 540.65 gr NaTB and 2764.03gr BA in 189.3lt of DI water.
2. Record pH and temperature from the pH meter.
3. Add 208.435 g of $\text{Al}(\text{NO}_3)_3$ salt to 500 mL of DI water and let it dissolve completely.

4. Add the solution from Step 2 into the corrosion tank. Allow solution to mix. Record pH and temperature from the pH meter.
5. Add 66.699 g of NaOH salt to 500 mL of DI water and let it dissolve completely.
6. Add the solution from Step 4 into the corrosion tank. Allow solution to mix. Record pH and temperature from the pH meter.
7. Collect samples for PSD and settling rate experiments.

This recipe was used to prepare the chemical injections C-1, C-2 in test HT-1104.

6.2.4 *Representative salt surrogate 2*

This recipe produces 19.8 g of Al (equivalent to 44.0 g of AlOOH) of non-diluted representative salt surrogate. This recipe differs from the previous recipe because 50 more gallons cannot be injected into the loop, the solution in the loop may not be drained, and the solution in the loop may not be used as the solution to mix this recipe.

1. Make 800 mL borated buffer solution at target pH of 7.2. Record pH and temperature from the pH meter.
2. Add 68.750 g of $\text{Al}(\text{NO}_3)_3$ salt to 100 mL of DI water and let it dissolve completely. Record the mixing rate and/or technique.

3. Add the solution from Step 2 into the solution from Step 1. Record pH and temperature from the pH meter.
4. Add 22.000 g of NaOH salt to 100 mL of DI water and let it dissolve completely. Record the mixing rate and/or technique.
5. Add the solution from Step 4 into the solution from Step 3. Record pH and temperature from the pH meter.
6. Collect samples for PSD and settling rate experiments.
7. Make 3 more 1 lt batches.

This recipe was used as the final injection C-3 in test HT-1104

6.2.5 *Representative salt surrogate 3 (ARL)*

The preparation procedure for this representative salt surrogate is that of Alden Research Laboratory (ARL). This recipe will create 2.1 g of AlOOH per liter of solution or 198.73 g of AlOOH in total which is equivalent to 89.36g of Al corrosion product.

1. Make borated buffer solution at target pH of 7.2 in the corrosion tank with 94.63lt. Record pH and temperature from the pH meter
2. Add 1242.0845 g of $\text{Al}(\text{NO}_3)_3$ salt to 2 lt of DI water and let it dissolve completely.
3. Add the solution from Step 2 into the corrosion tank. Allow solution to mix. Record pH and temperature from the pH meter.

4. Add 397.467 g of NaOH salt to 1 lt of DI water and let it dissolve completely.
5. Add the solution from Step 4 into the corrosion tank. Allow solution to mix. Record pH and temperature from the pH meter.
6. Collect samples for PSD and settling rate experiments.

This recipe was used to prepare the chemical injections C-1, C-2 in test HT-1201RE-2

7 TEST REALIZATION

The parameters varied during the head-loss tests were the following:

- The screen approach velocity
- The water temperature and chemistry (pH)
- The type(s) and quantities of debris in the debris bed

In the past, most of the tests were conducted in high approach velocity conditions, approximately 0.03 m/s. After modifications of sump strainer size in PWRs, the approach velocity to the sump strainer was reduced by an order of magnitude, approximately 0.001 ~ 0.003 m/s. Howe et al. [8] and Kim et al. [9] conducted several head loss tests at the approach velocity of 0.003 m/s. In the present study, an approach velocity of 0.0006 m/s (0.002ft/sec) was selected for an extremely slow power plant condition. A PCI strainer design was used as previous head loss tests and debris bypass tests conducted by Lee et al. [10], [11].

In order to acquire the data of interest a monitoring system was implemented and a test generic test procedure was followed.

7.1 Monitoring System

The monitoring system includes the following procedures and instrumentation:

- Flow rate (or approach velocity), temperature, and pressure-loss (or head-loss) measurements were taken every second with a data acquisition system.
- Test section images were taken every 10 seconds with a mounted camera.
- At least 10 minutes of clean-strainer data were recorded prior to the first debris addition.
- Approximate debris bed thickness measurements are to be taken:
 - 1 When the conventional debris bed is fully formed
 - 2 When the acceptance criteria of the conventional debris bed is met. The acceptance criterion for bed stability varies based on the differential pressure measurement as presented in Table 7.1.
 - 3 When the acceptance criteria for each chemical precipitate debris batch is met.
 - 4 At the end of the test.
- At least 50 mL loop solution samples are to be taken at the sample port downstream of the strainer before each chemical batch addition.
- At least 50 mL samples are to be taken at the sample port upstream of the strainer after each chemical addition when the suspended chemical load visually reaches the location of the sample port.

- Turbidity, pH, and temperature from the pH meter are to be measured for each sample. These samples are also to be submitted for ICP analysis to obtain a standard suite of elemental concentrations associated with AlOOH.
- Also, any abnormal debris bed shape changes and other observations such as debris traversing from the introduction point to the screen faster than the flow rate are to be documented.

Table 7.1 Acceptance criteria

Differential Pressure		Acceptance Criteria	
Measurement			
< 0.3 psid/2kPa		Change in pressure loss of < 0.003psid/0.02kPa per hour	
≥ 0.3 psid/2kPa		Change in pressure loss of < 1% per hour	

7.2 Generic Test Procedure

The generic test procedure to acquire the experimental data was as follows:

- Fill up the loop (356lt) with water of specified acidity. For a 7.2 pH 1.0164 kg of NaTB, and 5.1963 kg of Boric Acid are added to 356lt of DI water in one of the corrosion tanks (CT-R designates the red corrosion tank) and mixed until the chemicals are fully dissolved).
- Heat up the loop to 85°C and have the water circulate at 0.03m/s
- Inject debris batch B-1 and debris batch B-2 at predetermined time intervals to create the conventional debris bed. B-1 at 10 minutes after test initiation and B-2, 60 minutes after B-1.
- Have the solution circulate until the conventional debris bed is fully formed and stable. Apply the acceptance criteria specified in Table 7.1.
- Cool off the loop till room temperature. (During this phase, sharp rises in Pressure Drop were noticed in several experiments. It is considered to be the effect of the change in fluid viscosity due to the temperature drop. The viscous term in corellation-6224 predicts that behavior)
- If bed is stable reduce velocity to 0.0006m/s.
- Wait for debris bed to stabilize at this approach velocity.
- If bed is stable inject chemical precipitates. Chemical injection includes two sequential batches C-1, C-2. Bed must be stable before each injection.

- If bed is stable conduct flow sweeps. Flow sweeps are sequential changes in flow rate aimed to study the behavior of the debris bed and specifically phenomena like hysteresis and the plasticity of the debris bed. Flow sweeps are to be conducted after the last chemical batch acceptance criteria are met. Once the desired flow sweep velocity is achieved, the velocity and corresponding pressure loss must be stable at a constant value (within reason) for at least 4 minutes as specified in Table 7.2.
- If bed is stable and pressure allows for it, meaning that it is less than the operational limit of 31kPa proceed with final injection. If not terminate.
- Final injection.
- Terminate Test. The test is to be terminated after the final injection.

Table 7.2 Flow sweeps

Flow Sweep	Velocity	Duration
N/A	0.0006 m/s *	N/A
FS-A	0.0003 m/s	4 minutes
FS-B	0.0006 m/s	4 minutes
FS-C	0.0009 m/s	4 minutes
FS-D	0.0012 m/s	4 minutes
FS-E	0.0003 m/s	4 minutes
FS-F	0.0006 m/s	4 minutes

*Approach velocity before the beginning of flow sweeps.

8 RESULTS

Of the multitude of experiments conducted four were analyzed for the purpose of this study. Namely experiments: HT-1102b, HT-1103, HT-1104 and HT-1201RE-2. This chapter will present the results of these experiments.

8.1 HT-1102b

The following Table 8.1 presents the materials used in experiment HT-1102b

Table 8.1 Materials used in head loss test HT-1102b

Batch	Material	Quantity (g)	Conditions
B-1	Dirt	4.30	Dry particles
	Tin Powder (LX-2176)	28.00	Dry particles
	Acrylic Powder (LX-2180)	47.20	Dry particles
	CalSil	5.00	Blended/ Sieved
B-2	NUKON	6.00	One-side Baked
C-1	Al	9.97	In-Situ Chemical
C-2	Al	5.14	In-Situ Chemical
C-3	AlOOH	10.00	WCAP

The steps conducted during test HT-1102b were as follows:

1. The head loss test loop was filled with BB DI water (target pH = 7.2) from corrosion tank 1 until the water level in the top water tank reached the 23" mark.
355.83lt in total.
2. Measurements of pH and EC for the DI water, BB-DI water in the corrosion tank, and buffered borated DI water in the test loop were recorded.
3. Instrument calibrations verification was performed.
4. The flow rate in the loop was set to 0.03 ± 0.001 m/s and the heaters were turned on.
5. Once reached 85°C, the heaters were connected to the temperature controls to maintain the temperature within ± 3 °C.
6. Pressure drop was checked for stability following the criterion in Table 7.1.
7. The debris constituents of B-1 were uniformly mixed in a plastic container as described in Section 6.1.1
8. The data acquisition system was triggered 10 minutes before the B-1 injection.
9. B-1 was injected into the loop water tank.
10. Water in the loop was circulated for 1 hour.
11. Once stability was achieved, B-2 was injected into the loop water tank.
12. Approximately 16 hours after the injection of B-2 the heaters were turned off to allow the system to cool-down to room temperature.

13. A portable air conditioner unit (LG, Model # LP0814WNR, 115V, 8.0 A) was used to help cool-down the tank to ambient temperature. The AC unit was placed at the left corner of the loop tank blowing cold air on the outer metal surfaces of the loop tank.
14. Once the temperature of the loop reached room temperature (approximately 23 hours of cooling time) the approach velocity was adjusted to 0.0006 m/s.
15. Water in the loop was circulated for 3 hours, until stability was achieved.
16. C-1 and C-2 were injected and samples were taken. C-1, C-2 were produced as specified in section 6.2.1.
17. Water in the loop was circulated for approximately 47 hours, until stability was achieved.
18. Since the pressure drop increased after the In-situ chemicals injection, six flow sweeps were conducted. For each flow sweep, the velocity was held constant for 4 minutes.
19. Water in the loop was circulated for approximately 25 hours, to insure stability was achieved
20. WCAP aluminum precipitate (C-3) was injected via a 60 mL syringe over the course of 9 minutes. This final injection was produced as specified in section 6.2.2. Prior to test conclusion a batch of WCAP aluminum precipitate was injected to demonstrate the conventional debris bed could filter WCAP aluminum precipitate. This batch was added after the pressure loss was stabilized.

21. One sample (W-1-D) was taken from the downstream of the strainer 14 minutes before the WCAP injection. Two upstream samples (W-1-U and W-1-U-2) were taken 5 and 50 minutes respectively after W-1 injection.
22. The approach velocity started to decrease, approximately 8 minutes after WCAP injection, and reached zero (No Flow) 39 minutes after WCAP injection.
23. Another Upstream sample (W-1-U-3 (Final)) was taken 211 minutes after WCAP injection.
24. An attempt to increase the approach velocity led to a pressure drop increase, the pressure drop was above the test operation limit.
25. Test was terminated

The results from head loss test HT-1102b were divided into seven different phases: P-1, P-2, P-3, P-4, P-5, P-6, and P-7. Information about these phases can be found in Table 8.2.

Table 8.2 Phases for HT-1102b

Phase #	Description	Loop approach velocity	Loop Temperature
P-1	Injection of B-1 into the tank	0.03 m/s	85 °C
P-2	Injection of B-2 into the tank	0.03 m/s	85 °C
P-3	Cooling the system	Varies	85-23 °C
P-4	Velocity Change/Adjustment	0.03 to 0.0006 m/s	~23 °C
P-5	In-Situ Chemical Injection	0.0006 m/s	~23 °C
P-6	Flow Sweeps	Varies	~23 °C
P-7	WCAP Injection	0.0006 to 0.00 m/s	~23 °C

A plot of the pressure drop and approach velocity at the strainer during the entire head loss test HT-1102b is presented in Figure 8.1. The temperature profile recorded throughout the test duration is plotted in Figure 8.2. Flow sweeps for this test are presented in Figure 8.3. The vertical lines in the figures are used to indicate the different phases of the test. Each phase is labeled by numbers.

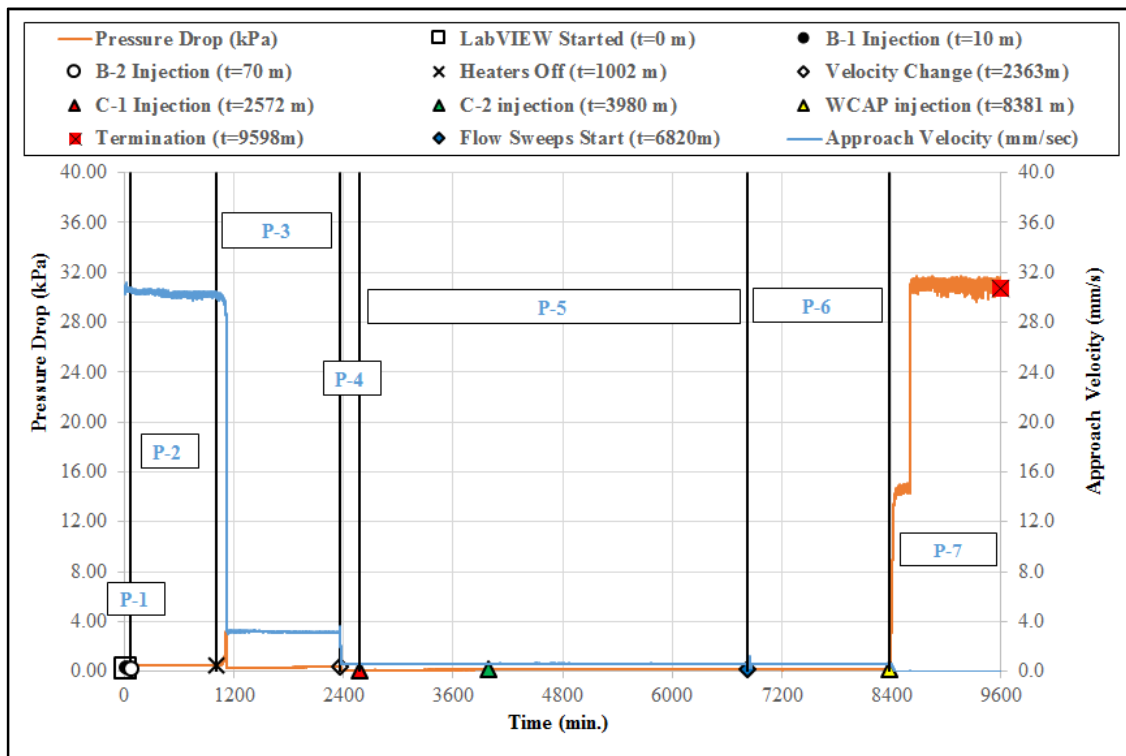


Figure 8.1 Pressure drop and flow rate for test HT-1102b

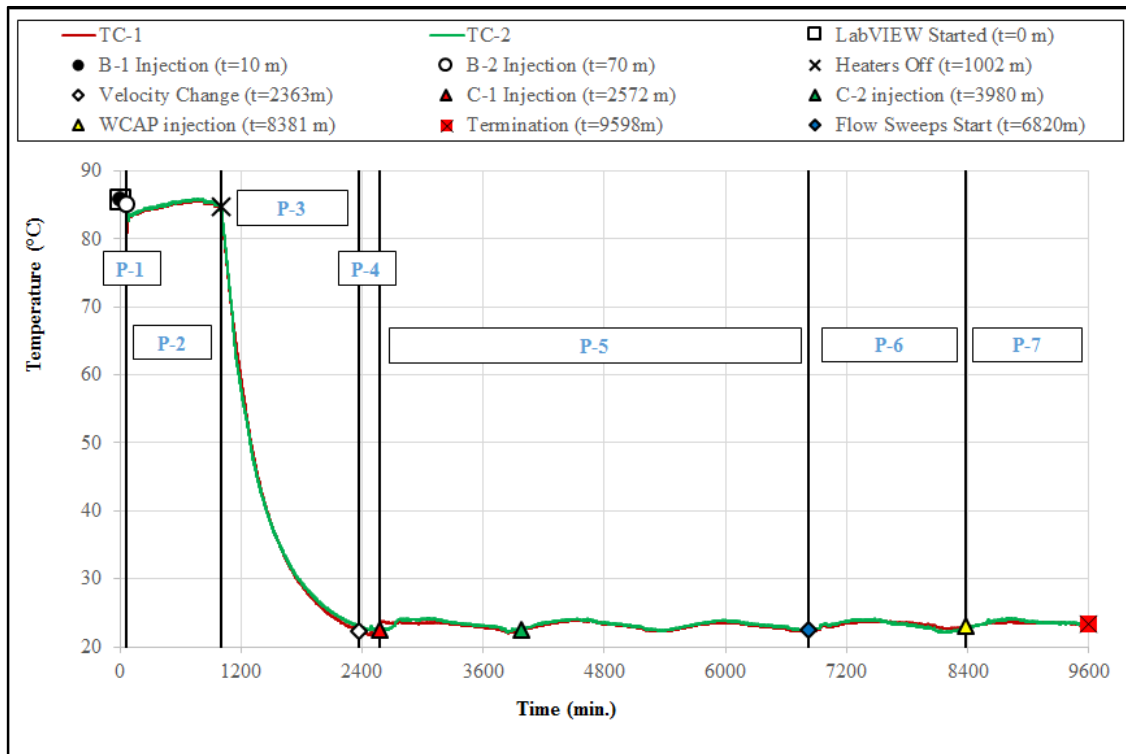


Figure 8.2 Temperature read by thermocouples for test HT-1201b

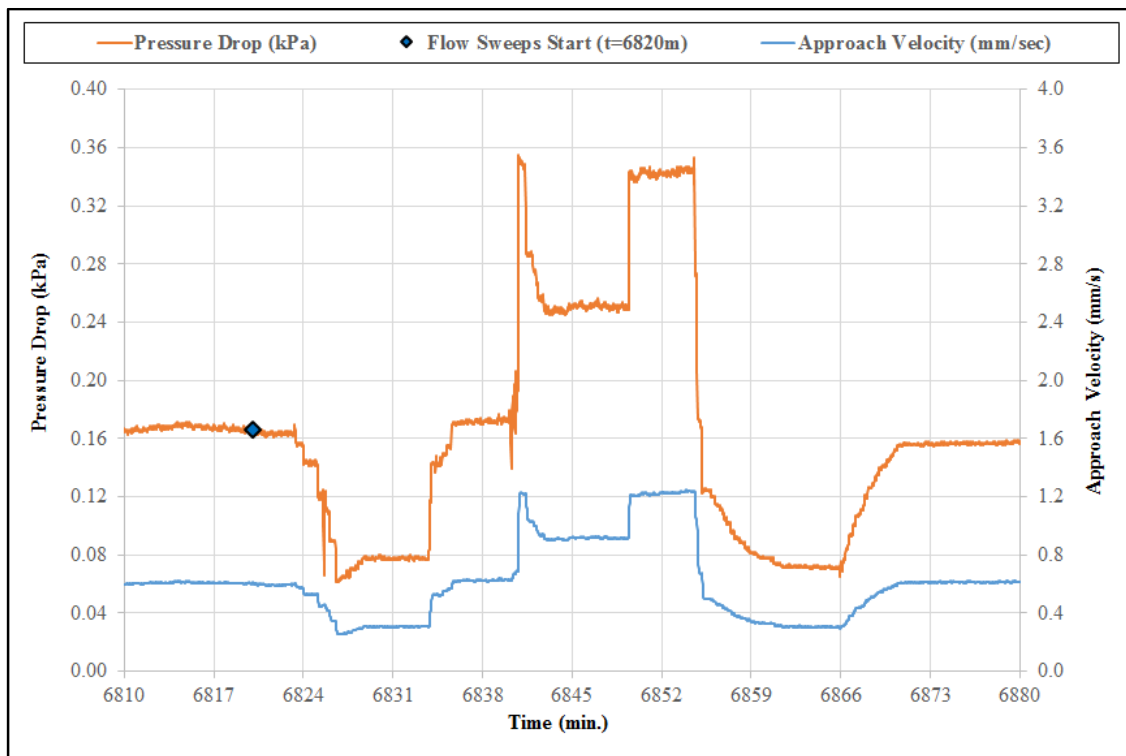


Figure 8.3 Flow sweeps for test HT-1102b

8.2 HT-1103

The following Table 8.3 presents the materials used in experiment HT-1103

Table 8.3 Materials used in head loss test HT-1103

Batch	Material	Quantity (g)	Batch Volume (lt)	Conditions
B-1	Dirt	4.3	1	Dry particles
	Tin Powder (LX-2176)	28.0		Dry particles
	Acrylic Powder (LX-2180)	47.2		Dry particles
	CalSil	5.0		Blended/ Sieved
B-2	NUKON	6.0	15.14	One-side Baked
C-1	Al	9.9	125	WCAP (Diluted)
C-2	Al	5.1	64.3	WCAP (Diluted)

The generic steps conducted during HT-1103 were as follows:

1. The head loss test loop was filled with buffered borated DI water (target pH = 7.2) from corrosion tank 1 until the water level in the top water tank reached the 23" mark. 355.83lt in total.

2. Measurements of pH and electrical conductivity for the DI water, buffered borated (BB) deionized (DI) water in the corrosion tank, and buffered borated DI water in the test loop were recorded.
3. Instrument calibrations verification was performed.
4. The flow rate in the loop was set to 0.03 ± 0.001 m/s and the heaters were turned on.
5. Once reaching 85°C, the heaters were connected to the temperature controls to maintain the required temperature
6. Pressure drop was checked for stability.
7. The debris constituents of B-1 were uniformly mixed in a plastic container as described in Section 6.1.1
8. B-1 was injected into the loop water tank.
9. Water in the loop was circulated for 1 hour.
10. Pressure drop was checked to ensure debris bed stability
11. B-2 was injected into the loop water tank.
12. Approximately 17 hours after the injection of B-2 the heaters were turned off to allow the system to cool-down to room temperature.
13. A portable AC unit (LG, Model # LP0814WNR, 115V, 8.0 A) was used to help cool-down the tank to ambient temperature.
14. Once the temperature of the loop had reached room temperature, approximately 22 hours of cooling, the debris bed was checked for stability following the criteria described in Table 7.1 and the approach velocity was decreased to 0.0006m/s

15. 189.3lt of loop solution were directly drained from the main loop tank into the corrosion tank.
16. The chemical injection solution (C-1, C-2) was prepared as specified in section 6.2.2. The 1.5-L WCAP solution was added to the tank and pump P-C1-1 was turned on to promote mixing.
17. 3.7 hours after the approach velocity was decreased, C-1 was injected into the main-loop tank using the corrosion-tank injection pump P-C1-2. One sample downstream of the test section (C-1-D) was taken 12 minutes before C-1 injection, and two samples upstream of the test section (C-1-U and C-1-U-2) were taken 2 and 3 hours, respectively, after C-1 injection.
18. C-2 was injected 23 hours after C-1, a downstream sample (C-2-D) was taken 25 minutes before the injection of C-2, and two upstream samples (C-2-U and C-2-U-2) were taken 2 and 3 hours, respectively, after C-2 injection.
19. Water in the loop was circulated for approximately 27.9 hours after C-2 injection, until stability was achieved.
20. Six velocity sweeps were carried out: FS-A, FS-B, FS-C, FS-D, FS-E, and FS-F.
21. After the flow sweeps, water in the loop was circulated for approximately 3 hours before terminating the test.
22. Two final samples (Final-D and Final-U) were taken right before the test termination.
23. Test was terminated.

The results from head loss test HT-1103 have been divided into six different phases: P-1, P-2, P-3, P-4, P-5, and P-6. Information about these phases can be found in Table 8.4.

Table 8.4 Phases for HT-1103

Phase #	Description	Loop approach velocity	Loop Temperature
P-1	Injection of B-1, B-2 into the tank	0.03 m/s	85 °C
P-2	B-2 to Heaters off	0.03 m/s	85 °C
P-3	Cooling the system to Velocity Change	0.03 m/s	85-25°C
P-4	Velocity Change to C-1 injection	0.3 to 0.0006 m/s	~25°C
P-5	C-1, C-2 to Flow Sweeps	0.0006 m/s	~25 °C
P-6	Flow Sweeps to END	0.0006 m/s	~25 °C

A plot of the differential pressure and approach velocity at the strainer during the entire head loss test HT-1103 is presented in Figure 8.4 . The temperature profile recorded throughout the test is plotted in Figure 8.5. The Flow sweeps are presented in Figure 8.6. The vertical lines in the figures are used to separate the different phases of the test. Each phase is labeled by numbers.

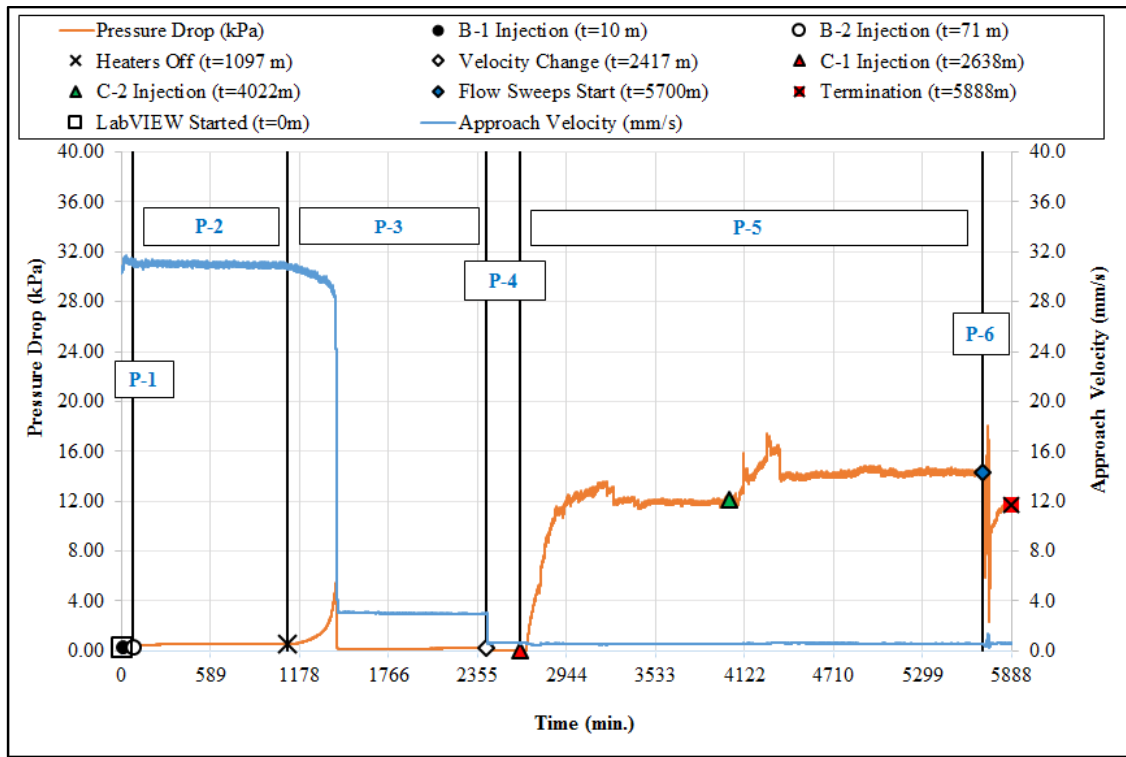


Figure 8.4 Pressure drop and flow rate through test section for test HT-1103

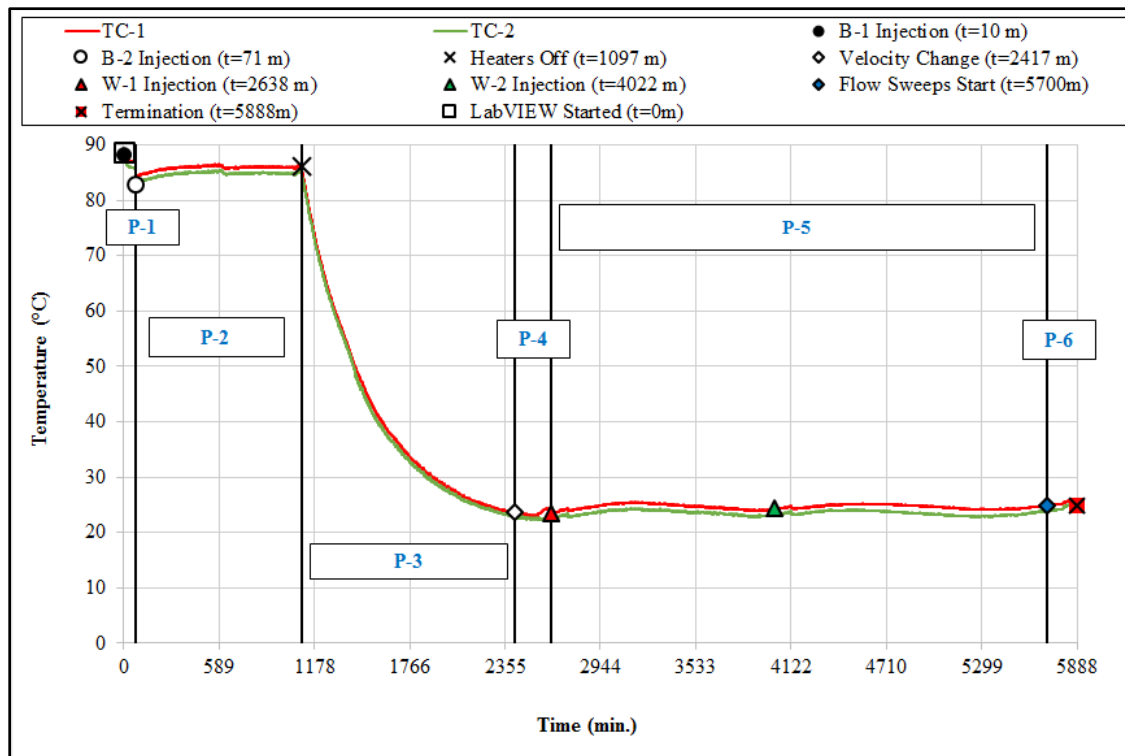


Figure 8.5 Temperature read by thermocouples for test HT-1103

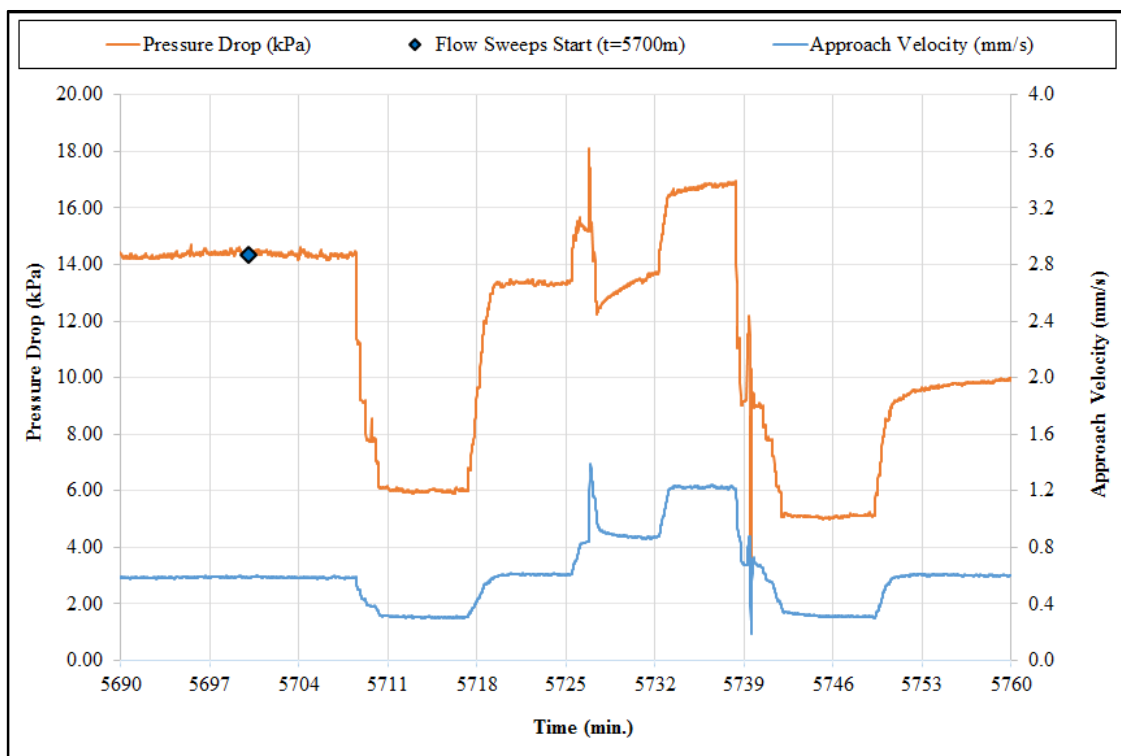


Figure 8.6 Flow sweeps for test HT-1103

8.3 HT-1104

The following Table 8.5 presents the materials used in experiment HT-1104

Table 8.5 Materials used in head loss test HT-1104

Batch	Material	Quantity (g)	Batch Volume (lt)	Conditions
B-1	Dirt	4.30	1	Dry particles
	Tin Powder (LX-2176)	28.00		Dry particles
	Acrylic Powder (LX-2180)	47.20		Dry particles
	CalSil	5.00		Blended/ Sieved
B-2	NUKON	6.00	15.14	One-side Baked
C-1	Al	9.60	125	Salt Recipe 1
C-2	Al	5.46	64.3	Salt Recipe 1
C-3	AL	19.80	4	Salt Recipe 2

The steps conducted during test HT-1104 where as follows:

1. The head loss test loop was filled with buffered borated (BB) DI water (target pH = 7.2) from corrosion tank 1 until the water level in the top water tank reached the 23" mark. 355.83lt in total.
2. Measurements of pH and electrical conductivity for the DI water, BB-DI water in the corrosion tank, and buffered borated DI water in the test loop were recorded.
3. Instrument calibrations verification was performed.
4. The debris constituents of B-1 were uniformly mixed in a glass container.
5. B-1 was injected into the loop water tank 10 minutes after the test initiation.
6. Water in the loop was circulated for 1 hour with an approach velocity of 0.3m/s.
7. B-2 was injected into the loop water tank.
8. Water in the loop was circulated for approximately 15 hours and acceptance criteria were met.
9. All insulation were removed.
10. All heaters were turned off.
11. The approach velocity was reduced to 0.03 m/s due to pressure drop increase
12. Water in loop was circulated in the loop for approximately 25 hours
13. The water in the loop reached ambient temperature ± 3 °C, and acceptance criteria were met.
14. The approach velocity was reduced to $0.0006 \text{ m/s} \pm 0.0001 \text{ m/s}$.
15. Water in loop was circulated in the loop for 3 hours
16. The required volume of 189.3 lt was drained from the loop tank.
17. Water in the loop was circulated for about 41 minutes.

18. Batches C-1, C-2 were prepared according to the procedure presented in section 6.2.3.

19. The first chemical sub-batch C-1 (125lt) was injected into the loop.

20. Sample C-1-D was taking 3 minutes before C-1 injection, and Sample C-1-U-1 and C-1-U-2 were taking 2 and 3 hours after C-1 injection respectively.

21. Stability criteria was achieved.

22. The second chemical sub-batch C-2 (64.3lt) was injected into the loop approximately 34 hours after C-1 Injection

23. Stability criteria was achieved.

24. Flow sweeps were conducted 26 hours after C-2 Injection.

25. Batch C-3 was prepared according to the procedure presented in section 6.2.4.

26. The Final injection batch C-3 was injected approximately 24 hours after the flow sweeps.

27. Water in the loop was circulated for approximately 1 hour, before we reached operational limit.

28. Test was terminated.

The results from head loss test HT-1104 have been divided into 7 different phases: P-1, P-2, P-3, P-4, P-5, P-6 and P-7. Information about these phases can be found in Table 8.6.

Table 8.6 Phases for HT-1104

Phase #	Description	Loop approach velocity	Loop Temperature
P-1	Injection of B-1 into the tank	0.03 m/s	85°C
P-2	Injection of B-2 into the tank	0.03 m/s	85°C
P-3	Cooling the system	0.03 m/s	85°C-25°C
P-4	Velocity Change/Adjustment	0.03 to 0.0006 ft/s	~25°C
P-5	Salt Recipe (C-1 & C-2)	0.0006 ft/s	~25°C
P-6	Flow Sweeps	Varies	~25°C

A plot of the differential pressure and approach velocity through the strainer during the entire head loss test HT-1104 is presented in Figure 8.7. The temperature profile recorded throughout the test duration is plotted in Figure 8.8. Flow sweeps for this test are presented in Figure 8.9. The vertical lines in the figures are used to separate the different phases of the test. Each phase is labeled by numbers.

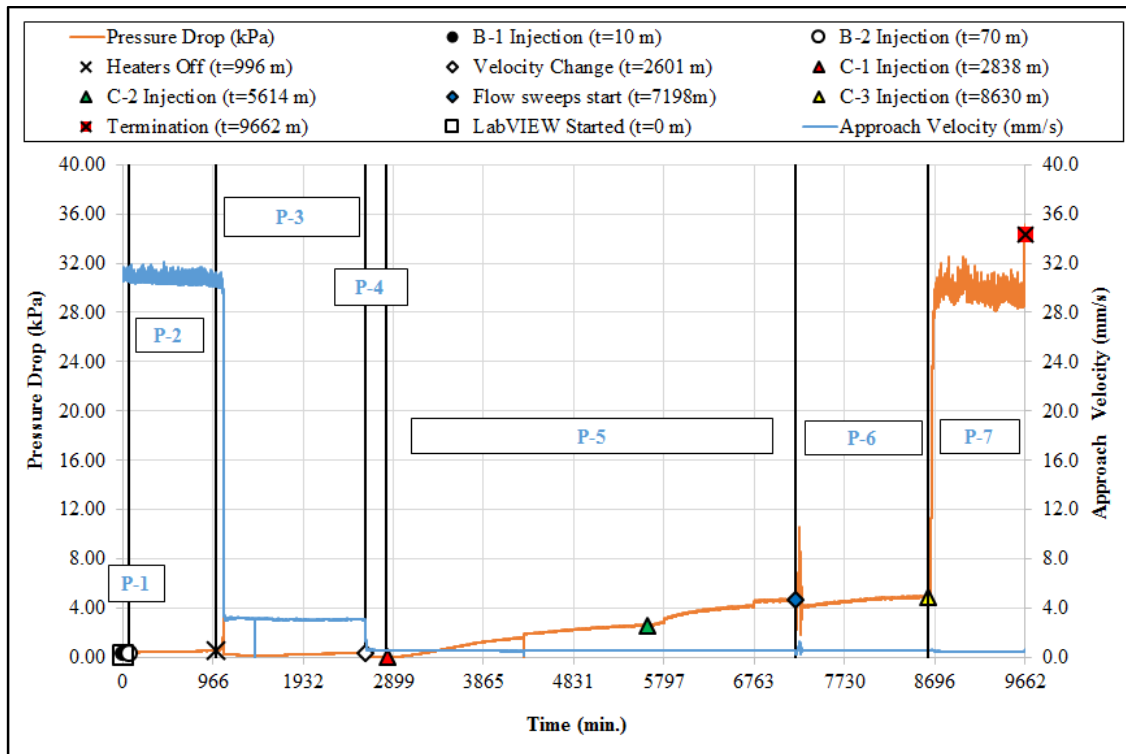


Figure 8.7 Pressure drop and flow rate through test section for test HT-1104

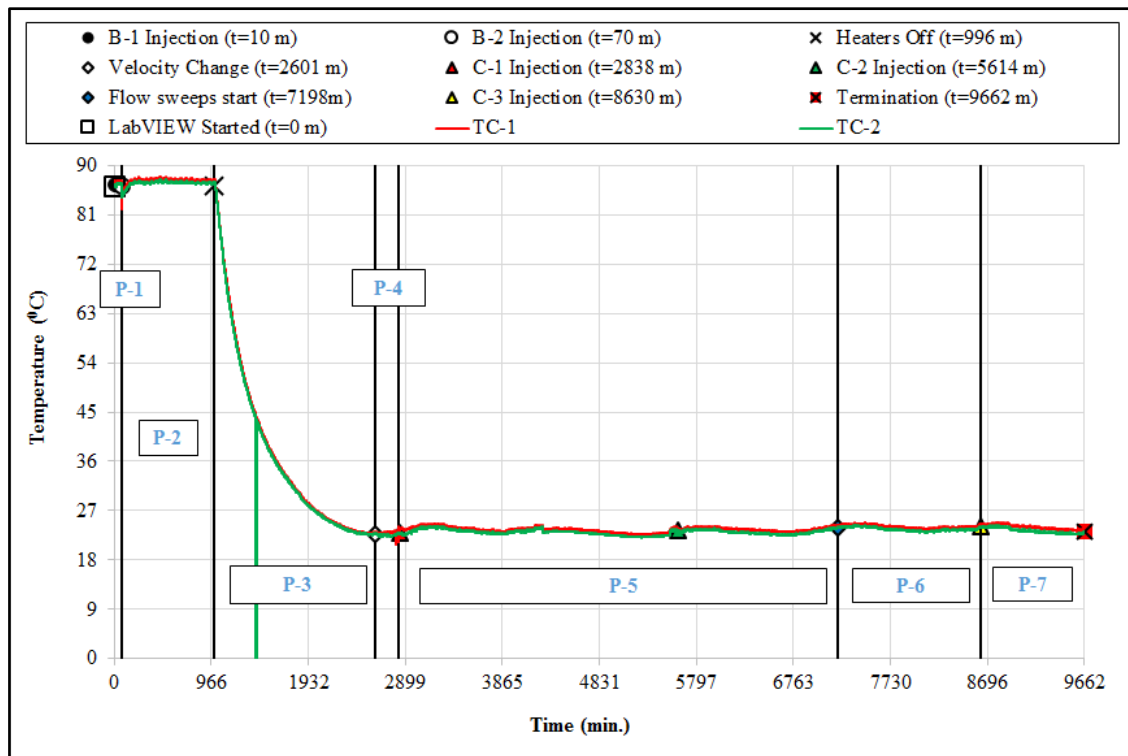


Figure 8.8 Temperature read by thermocouples for test HT-1104

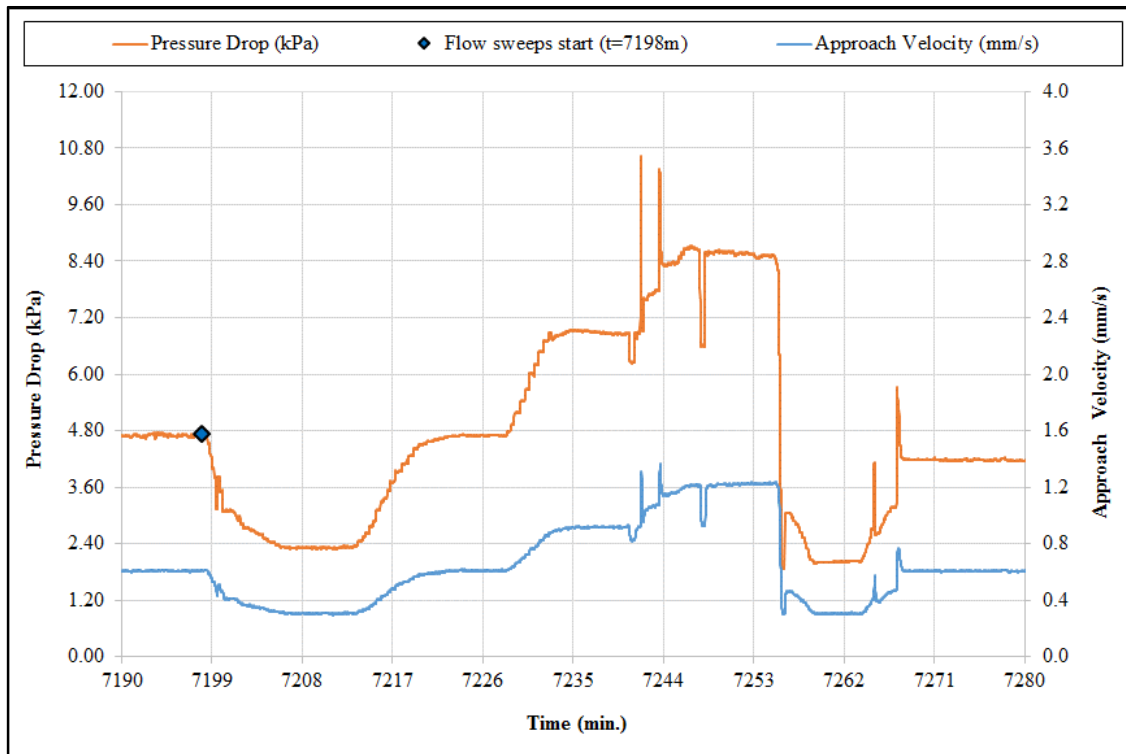


Figure 8.9 Flow sweeps for test HT-1104

8.4 HT-1201RE-2

The following Table 8.7 presents the materials used in experiment HT-1201RE-2.

Table 8.7 Materials used in head loss test HT-1201RE-2

Batch	Material	Quantity (g)	Batch Volume (lt)	Conditions
B-1	Dirt	4.30	1	Dry particles
	Tin Powder (LX-2176)	28.00		Dry particles
	Acrylic Powder (LX-2180)	47.20		Dry particles
	CalSil	5.00		Blended/ Sieved
B-2	NUKON	6.00	15.14	One-side Baked
C-1	Al	10.22	10.71	Salt Recipe (ARL)
C-2	Al	5.13	5.37	Salt Recipe (ARL)
C-3	Al	4.5	1	WCAP-16530

The steps conducted during test HT-1201RE-2 were as follows:

1. The head loss test loop was filled with buffered borated (BB) DI water (target pH = 7.2) from corrosion tank 1 until the water level in the top water tank reached the 23" mark. 355.83lt in total.
2. Measurements of pH and electrical conductivity for the DI water, BB-DI water in the corrosion tank, and buffered borated DI water in the test loop were recorded.
3. Instrument calibrations verification was performed.
4. The flow rate in the loop was set to 0.03 ± 0.001 m/s and the heaters were turned on.
5. Once reached 85°C, the heaters were connected to the temperature controls to maintain the temperature within ± 3 °C.
6. Pressure drop was checked for stability following the criterion in Table 7.1.
7. The debris constituents of B-1 were uniformly mixed in a plastic container as described in Section 3.1.1
8. The data acquisition system was triggered 10 minutes before the B-1 injection.
9. B-1 was injected into the loop water tank.
10. Water in the loop was circulated for 1 hour, which is more than 6 pool turnovers.
11. Once stability was achieved, B-2 was injected into the loop water tank.
12. Approximately 18 hours after the injection of B-2 the heaters were turned off to allow the system to cool-down to room temperature.
13. A portable air conditioner unit (LG, Model # LP0814WNR, 115V, 8.0 A) was used to help cool-down the tank to ambient temperature. The AC unit was placed

at the left corner of the loop tank blowing cold air on the outer metal surfaces of the loop tank.

14. Once the temperature of the loop reached room temperature (approximately 26 hours of cooling time) the approach velocity was adjusted to 0.0006 m/s.
15. Water in the loop was circulated for approximately 4 hours, until stability was achieved.
16. C-1, C-2 were prepared as specified in section 6.2.5.
18. C-1 (10.7lt) was injected in 11 sub-batches over the course of 10 minutes with 1 minute increment between batches. Each batch was 1 liter in volume except for the first batch, it was 0.7 liter.
19. C-2 (5.4lt) was injected, 45 hours after C-1 Injection, in 6 sub-batches over the course of 6 minutes with 1 minute increment between batches. Each batch was 1 liter in volume except for the first batch, it was 0.37 liter.
20. Water in the loop was circulated for approximately 22 hours, until stability was achieved.
21. Six flow sweeps were conducted. For each flow sweep, the velocity was held constant for 4 minutes.
22. Water in the loop was circulated for approximately 5 hours, to insure stability was achieved
23. WCAP was injected. WCAP was prepared according to the procedure specified in section 6.2.2.
24. Samples were taken before and after each chemical injection.

25. Test was terminated 23 minutes after final injection.

The results from head loss test HT-1201RE-2 were divided into seven different phases: P-1, P-2, P-3, P-4, P-5, P-6, and P-7. Information about these phases can be found in Table 8.8.

Table 8.8 Phases for HT-1201RE-2

Phase #	Description	Loop approach velocity	Loop Temperature
P-1	Injection of B-1 into the tank	0.03 m/s	84 °C
P-2	Injection of B-2 into the tank	0.03 m/s	84 °C
P-3	Cooling the system	0.03 m/s	84-23°C
P-4	Velocity Change/Adjustment	0.03 to 0.0006 m/s	~23 °C
P-5	Salt Recipe (C-1 & C-2)	0.0006 m/s	~23-21 °C
P-6	Flow Sweeps	Varies	~23-21 °C
P-7	WCAP (C-3)	0.0006 to 0.00m/s	~22°C

A plot of the pressure drop and approach velocity at the strainer during the entire head loss test HT-1201RE-2 is presented in Figure 8.10. The temperature profile recorded throughout the test duration is plotted in Figure 8.11. The flow sweeps are presented in Figure 8.12. The vertical lines in the figures are used to separate the different phases of the test. Each phase is labeled by numbers.

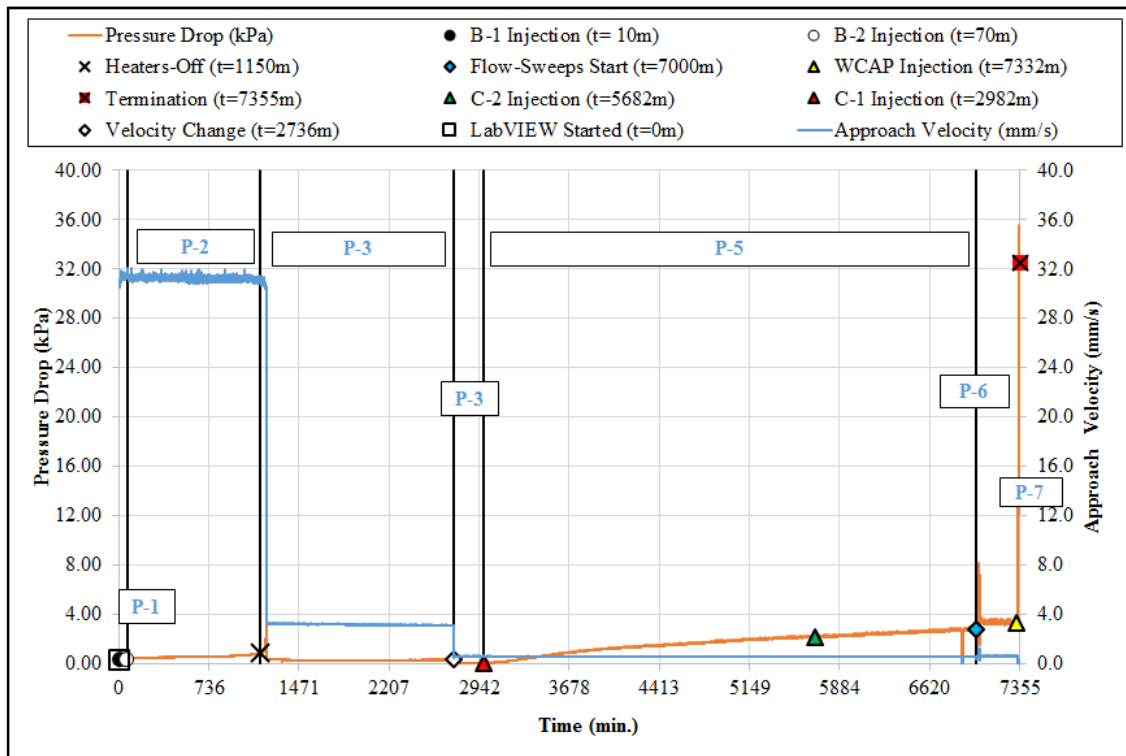


Figure 8.10 Pressure drop and flow rate through test section for test HT-1201RE-2

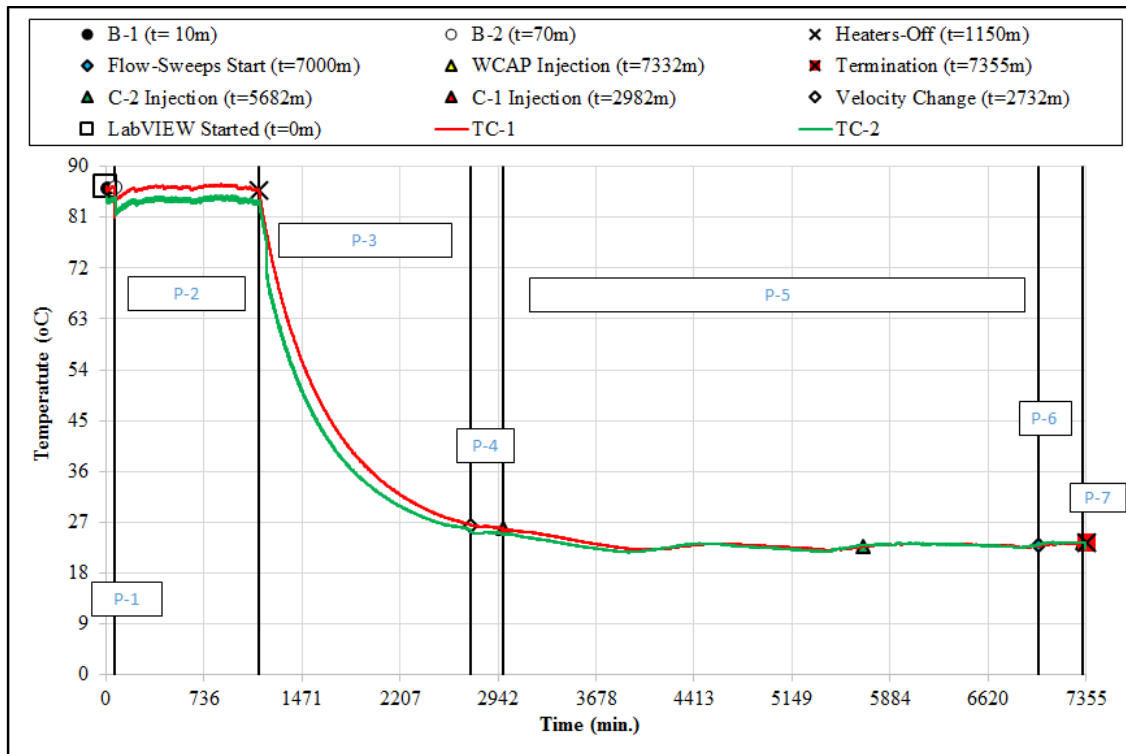


Figure 8.11 Temperature read by thermocouples for test HT-1201RE-2

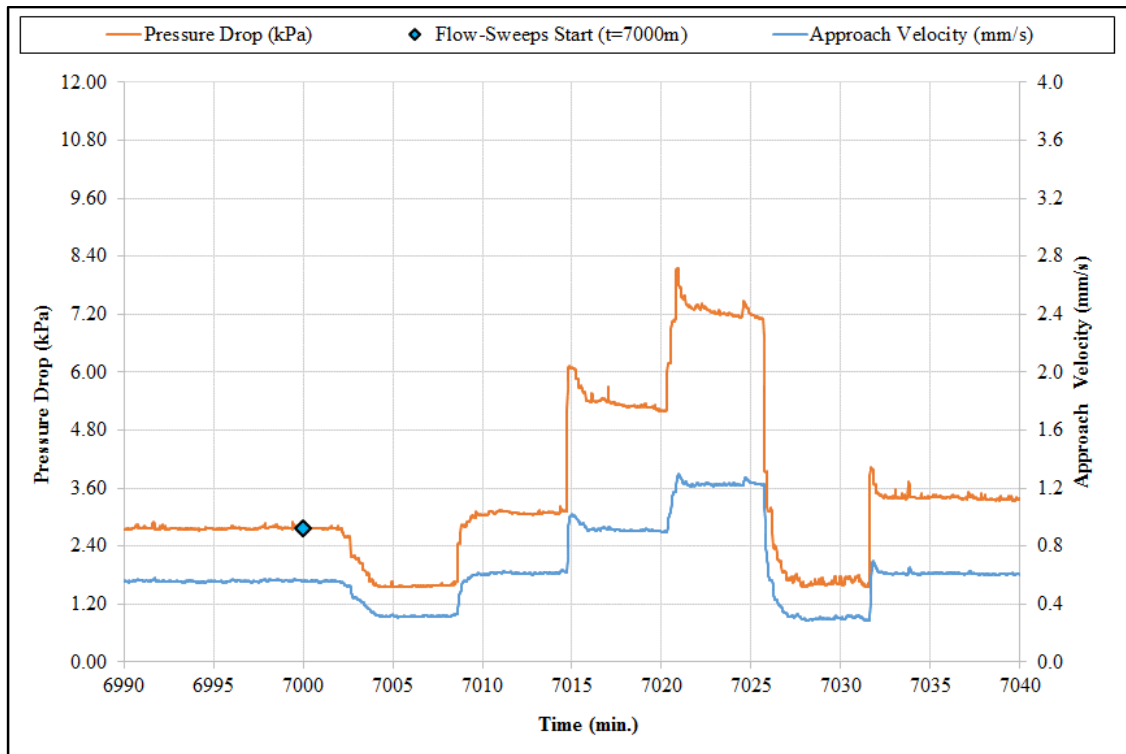


Figure 8.12 Flow sweeps for test HT-1201RE-2

9 ANALYSIS

- Four head loss experiments (HT-1102b, HT-1103, HT-1104 and HT-1201RE-2) were performed with different chemical precipitates:
- HT-1102b used in-situ Al precipitate (section 6.2.1) for its chemical injections and WCAP (section 6.2.2) was used for the final injection.
- HT-1103 used WCAP (section 6.2.2) for its chemical injections. There was no final injection in this test.
- HT-1104 used salt surrogate 1 (section 6.2.3) for its chemical injections and salt surrogate 2 for its final injection (section 6.2.4).
- HT-1201RE-1 used salt surrogate 3 (section 6.2.5) for its chemical injections and WCAP (section 6.2.2) was used for its final injection.
- The total mass of Al injected into the loop for each test during the chemical injections was the same. It was 15 g.
- For each test, the head loss test loop was filled with buffered borated deionized (BB-DI) water (target pH = 7.2) prepared with Boric acid and Sodium tetraborate.
- The loop temperature was maintained within 85 ± 3 °C at the approach velocity of 3 cm/s to the strainer.
- The debris constituents of B-1 were injected into the loop as a mixture. Water in the loop was circulated for 6 tank turnovers in order for B-1 to be uniformly mixed in the loop.

- Then, B-2 was injected into the loop.
- Approximately 16 hours after the injection of B-2 the heaters were turned off to allow the system to cool-down to room temperature. Once the temperature of the loop reached room temperature (26 ± 3 °C), the approach velocity was adjusted to 0.6 mm/s.
- Aluminum precipitates were injected in two batches (C-1, C-2). The water in the loop circulated until stability was achieved as specified in Table 7.1.
- Six flow sweeps were conducted at the end of the Al injection phase. For each flow sweep the velocity was held constant for 4 minutes as specified in Table 7.2.
- WCAP-163530 was injected additionally to confirm that the test debris bed responded to the chemical precipitate. Which means that the debris bed filtered WCAP particles and in turn caused a rise in pressure.

For each Al precipitate, a settling test was conducted for one hour, which is one of the traditional fine particle size characterizing technique [12] [13]. WCAP-16530 AlOOH, HT-1103, showed the greatest settling, which can be interpreted that it produced the largest particle size. HT-1102b and HT-1104 did not result in any visual sedimentation. HT-1201RE-2 showed less than 1% settling, which allowed little visual observation of sedimentation. Figure 9.1 presents an overview of the settling tests.



Figure 9.1 Settling tests. HT-1102b top left, HT-1103 top right, HT-1104 bottom left, HT-1201RE-2 bottom right.

9.1 Chemical Injection

Figure 9.2 presents the chemical injection phase of tests: HT-1102b, HT-1103, HT-1104 and HT-1201RE-2. For all tests the time of the first injection (C-1) has been shifted and set as time zero. Approach velocity during that time period was 0.6mm/s for all tests.

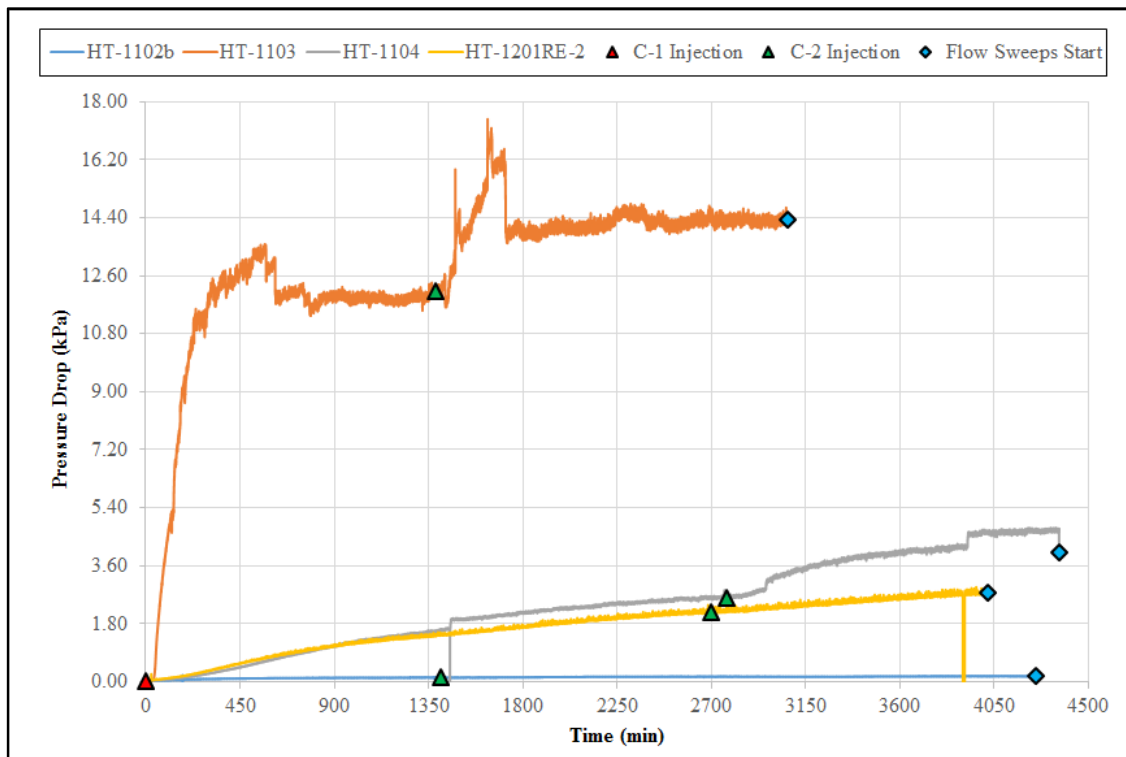


Figure 9.2 Pressure drop through the strainer for chemical injection phase for all tests.

The head loss through the debris bed just before Al precipitate injection C-1, through to C-2 and just before the flow sweeps start is summarized in Table 9.1.

Before Al precipitate injection, the conventional debris beds produced minor head loss compared to previous experiments [8], [9] . One of the reasons would be the extremely low approach velocity compared to the other power plant conditions. In each test, the first injection which was of greater mass caused greater additional head loss. For each test the more mass added the more additional head-loss was encountered. The change in head loss seems to be proportional to the mass of Al added but that is not the case. There is not a constant of proportionality, though there is definitely a trend.

In-situ Al precipitate injection of test HT-1102b resulted in the least head loss, which was negligible compared to the head loss caused by the other solutions. Salt Surrogate 1, Salt Surrogate 3 of tests HT-1104 and HT-1201RE-2, resulted in less head loss than WCAP-16530 by approximately one order and were comparable between themselves.

Based on the settling tests, we speculate that the faster settling Al WCAP-16530 solution used in test HT-1103, has a higher particle size. Consequently it produces greater head-loss. This makes sense because bigger particles are more likely to be detained by the conventional debris bed thus reducing the inter-fiber space inside the debris bed, blocking the flow path and raising the pressure drop.

Bahn et. AL [14] reported a 72.0 μm median particle size for a WCAP ALOOH surrogate solution of 11g ALOOH/lit concentration. Assuming that in our case the WCAP-16530 solution of test HT-1103 would have a median of similar if not larger

number, comparing that with the 30nm taken from Figure 6.11 (test HT-1102b) clearly demonstrates that the in-situ corrosion product production method, produces solutions with a much smaller particle size. This is in total agreement with the settling tests results, the head-loss responses and the qualitative explanation of the phenomena discussed here.

Table 9.1 Debris bed response to chemical injections

Test #	Pre Injection (kPa)	Chemical Injection 1 (kPa)	Chemical Injection 2 (kPa)
HT-1102b	0.0345	0.1310	0.1655
HT-1103	0.0067	12.1417	14.3411
HT-1104	0.0276	2.6131	3.9995
HT-1201RE-2	0.0138	2.1718	2.7619

9.2 Flow Sweeps

The head loss measured during the flow sweeps conducted after the chemical injections, is presented in Table 9.2.

Table 9.2 Debris bed response to flow sweeps

Velocity (m/sec)	HEAD LOSS (kPa)			
	HT-1102b	HT-1103	HT-1104	HT-1201RE-2
0.0006*	0.1655	14.2239	4.6746	2.7579
0.0003	0.0758	5.9778	2.2891	1.5720
0.0006	0.1724	13.3207	4.7022	3.0544
0.0009	0.2482	13.6240	6.8327	5.2952
0.0012	0.3378	16.7267	8.5357	7.2050
0.0003	0.0689	5.1090	2.0202	1.6203
0.0006	0.1586	9.8802	4.1713	3.3922

*Approach velocity before the beginning of flow sweeps.

All tests except HT-1103 exhibit a linear relation between Head loss and approach velocity as predicted by correlation 6224 for low approach velocities where the inertia term of the equation can be approximated to be equal to zero. The non-linearity can be attributed to changes to the morphology of the bed during the flow-sweeps.

The pressure drop response of the debris bed is presented in Figure 9.3.

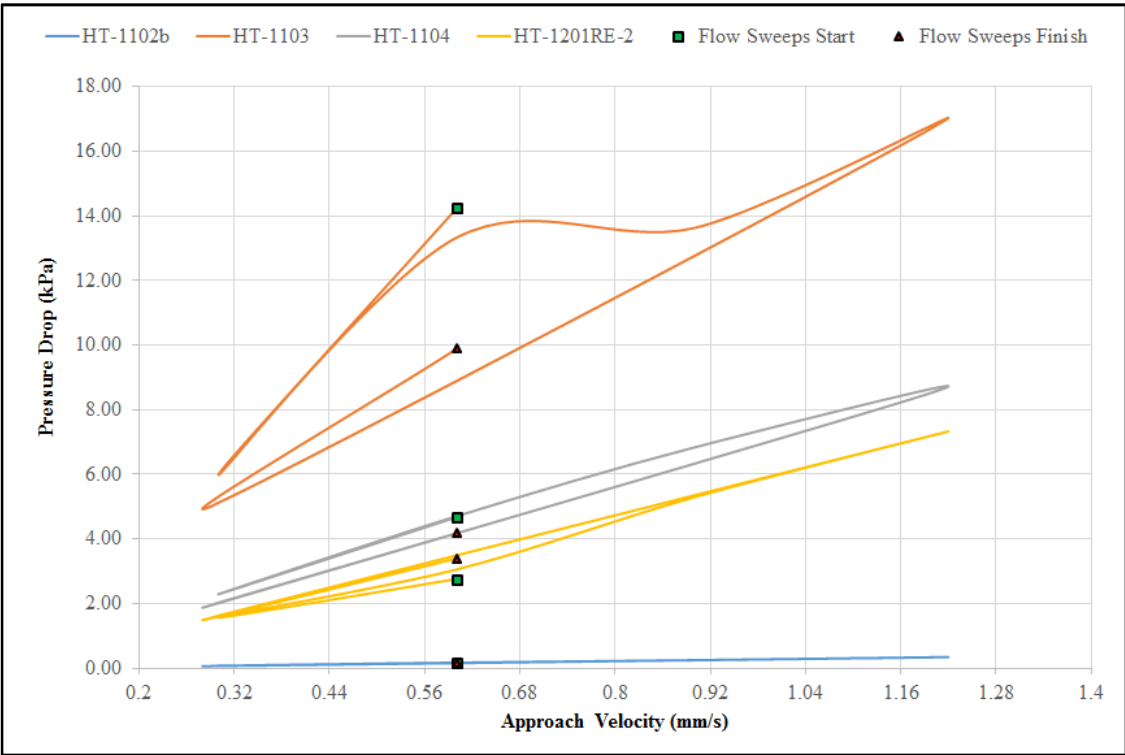


Figure 9.3 Proportional behavior of pressure drop through debris bed during flow-sweeps

9.3 Final Injection

The experiments in which a final injection was added in the end were HT-1102b, HT-1104 and HT-1201RE-2. The total mass of Al added was 4.5g, 19.80g and 4.5g respectively. In tests, HT-1102b and HT-1201RE-2, WCAP was used as the final injection. In test HT-1103, salt surrogate 2 was used as the final injection. Table 9.3 is the same as Table 9.1 with the added feature that this also presents the response of the debris bed after the final injection.

Figure 9.4 presents the response of the debris bed to the final injection against time. It presents the pressure drop through the strainer from the beginning of the flow sweeps until test termination. The time scale is shifted so that the time that the flow sweeps start is set to zero for all experiments. HT-1103 is included in the plot even though no final injection was done during that test as reference. The approach velocity during the phases presented in Figure 9.4 varied from 1.2mm/s to 0mm/s.

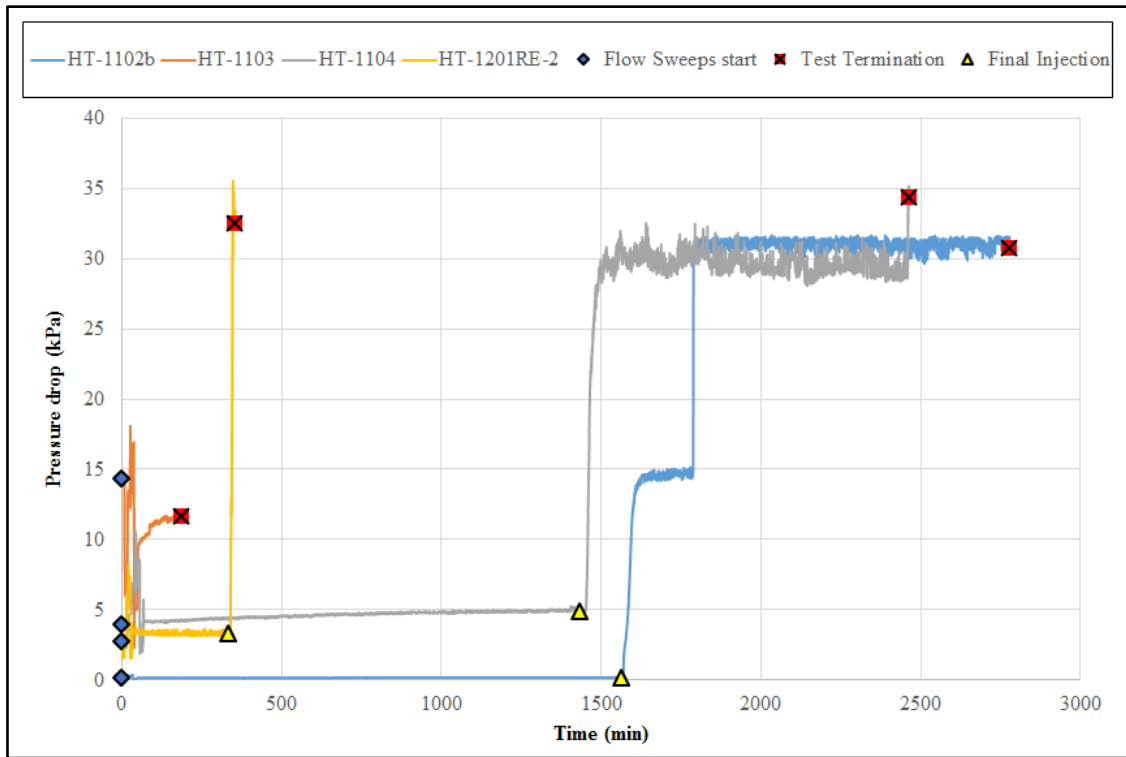


Figure 9.4 Debris bed response to final injection

The values of the pressure drop when the flow sweeps start are the same as those in the column “Chemical Injection 2” of Table 9.3 and Table 9.1.

Table 9.3 Debris bed response to chemical injections (Including WCAP)

Test #	Pre Injection (kPa)	Chemical Injection 1 (kPa)	Chemical Injection 2 (kPa)	Final Injection (kPa)
HT-1102b	0.0345	0.1310	0.1655	31.1643
HT-1103	0.0067	12.1417	14.3411	N/A
HT-1104	0.0276	2.6131	3.9995	28.7029
HT-1201RE-2	0.0138	2.1718	2.7619	32.7087

In all three experiments the debris bed responded to the final injection similarly to HT-1103. We can conclude that the debris beds filters WCAP and salt surrogate 2 very similarly and that for experimental purposes these solutions can be interchangeable.

10 CONCLUSIONS

Four head loss tests were analyzed in the present study in order to examine the behavior of a conventional debris bed in relation to the injection of five different chemical solutions. All of these solutions are considered to simulate the solution that is postulated to be produced during an actual LOCA at a PWR plant. Of these solutions the in-situ corrosion product is assumed to be the most representative of the specific plant conditions. Meaning that it simulates more accurately the postulated corrosion of Aluminum structures inside the containment sump of a PWR, which is considered to occur during an actual LOCA. At the same time it is the most expensive and time consuming to produce in relation to the other solutions examined in this thesis.

In the given conditions of debris bed constituents, In-situ Al precipitate (HT-1102b) resulted in the least additional head loss to the conventional debris bed prepared with NUKON® and other particulates. WCAP in test HT-1103 exhibited much greater head loss responses than all the other tests/solutions. Salt surrogate 1 and Salt surrogate 3 exhibited comparable head-loss responses between them with the first one being slightly higher. Both of them produced higher responses than the in-situ corrosion product. Summing up, three of the solutions produced head loss responses on the conservative side of the In-situ Corrosion product, with WCAP being on the far end and Salt surrogate 3 closer to the in-situ solution.

In the low approach velocity range of 0.3 to 0.6 mm/s, all the tests except HT-1103, resulted in linearly proportional head loss relation to velocity increase, which is

consistent with the predictions of existing correlations such as NUREG-6224. The non-linear behavior of debris bed HT-1103 can be attributed on changes in the morphology of the debris bed during the flow sweeps. In fact it is logical that these changes would occur during that experiment more so than the others because in that case more Al precipitate is assumed to have been detained inside the debris bed, thus the debris bed is more likely to re-arrange itself given the external stimuli.

In conclusion, this study suggests that Salt Surrogate 3 is the preferable surrogate in comparison to the other two options (WCAP, Salt Surrogate 1) in the case that the use of the in Situ-Corrosion product is considered to be, too time consuming or too expensive. The size of particles from different Al precipitate preparations as well as the total quantity of Al particulates being detained will be measured in future studies to obtain a quantitative result.

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